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American Journal of Science

NOVEMBER 1958

MINERALOGICAL AND CHEMICAL VARIATIONS IN THE WOLLASTON GRANITIC PLUTON, HASTINGS COUNTY, ONTARIO

AJIT KUMAR SAHA

ABSTRACT. The border zones of the Wollaston pluton (a well-foliated biotite-hornblende granite) and of an apophysal dyke of granite are relatively rich in silica and soda and poor in potash and the mafic constituents, compared with typical phases of these bodies. The content of soda and silica in the border zones increases exponentially as the outer contact is approached, whereas in the biotite paragneiss along the dyke contact it appears to be reduced, compared with the normal paragneiss. It is suggested that these variations can be explained by the diffusion of silica and soda in aqueous solution from the heated paragneiss into the adjacent granite magma at an early stage in the crystallization of the magma. It is suggested also that this process may account for the development of the so-called "basic fronts" in the country rock at granite contacts or as inclusions in the granite.

INTRODUCTION

Kennedy (1955, p. 491-492) has suggested the possibility of diffusion of interstitial water from the heated sediments into an adjacent intrusive magma, resulting in the enrichment of the marginal portions of the melt in water and "in the components from the surrounding country rock which the dense hot water fluid can readily dissolve and transport". As a possible example of such infusion of water and alkalies, he cited the ultrabasic intrusions at Kane Peak, Alaska (Kennedy and Walton, 1948).

In the course of a mineralogical and chemical study of the Wollaston granitic pluton (Hastings County, Ontario), it was found that the factual data can be explained adequately on the basis of the hypothesis of infusion of silica and alkalies in aqueous solution from the paragneissic country rocks into the granite magma.

GENERAL CHARACTERS OF THE WOLLASTON PLUTON

The Wollaston pluton is an elongated body (6 × 1¼ miles) of well-foliated biotite-hornblende granite, emplaced in crystalline limestone, biotite paragneiss and calcareous paragneiss (fig. 1). There are numerous inclusions and roof pendants of biotite paragneiss, all aligned sub-parallel to the foliation of the granite. Some of the roof-pendant patches and inclusions of biotite-hornblende paragneiss have been partially granitised to a grey coloured granite-gneiss. The primary origin of the foliation in the granite is indicated by the following characters: (1) parallelism of the trend of foliation with that of the granite margin, even where the granite contact is oblique to the foliation in the country rocks; (2) foliation in granite sweeping around the inclusions of biotite-hornblende paragneiss; (3) variations in the trend of foliation within short distances and (4) aplite veins cutting across the foliation of coarse gneissic granite. The granite shows a pronounced mineral lineation on the plane of foliation, plunging around 45° in a southerly direction; the

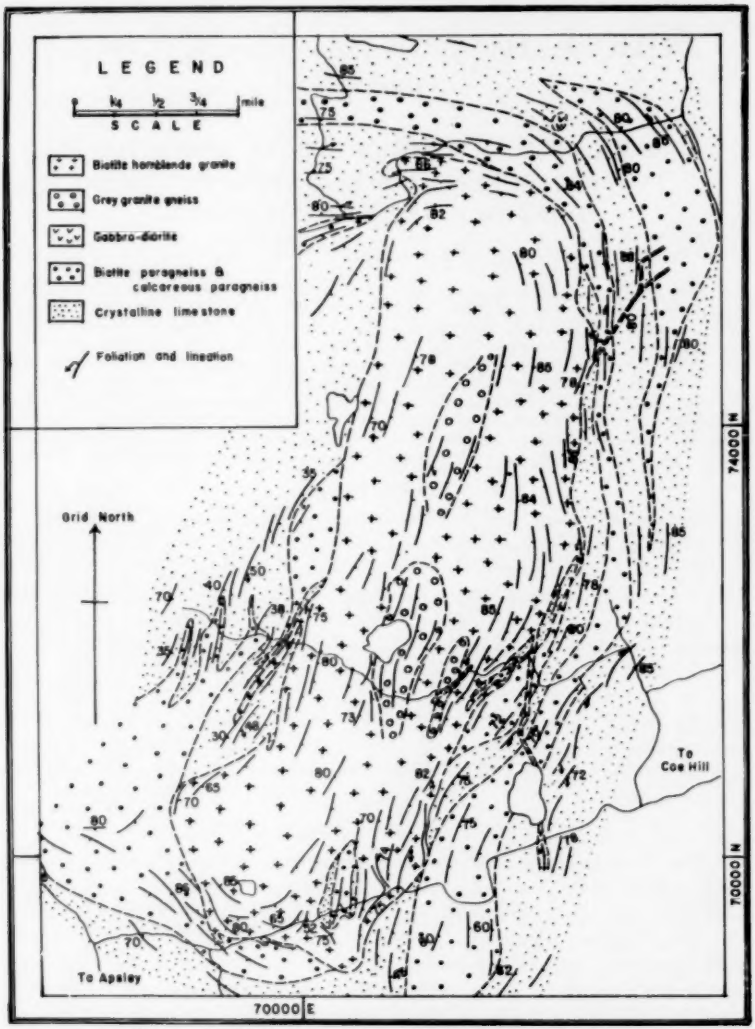

Fig. 1. Geological map of the Wollaston pluton, Ontario .

attitude of lineation in the granite is different from that in the surrounding country rocks. The pattern of foliation and lineation in the granite suggests that this north-south elongated pluton is a steeply east-dipping body with the western wall having a gentler dip than the eastern wall.

There are several narrow, long, offshooting dykes and sills of biotite-hornblende granite extending from the main body into the country rocks.

PETROLOGY

The biotite-hornblende granite, constituting the pluton, is made up essentially of plagioclase ($An_8 - An_{16}$), microcline (usually perthitic), quartz, biotite and hornblende, together with some magnetite, apatite and sphene as accessories; occasionally there is some interstitial calcite. Hornblende is absent in the near-border samples from the northern part of the pluton. Plagioclase is often myrmekitic.

Samples collected within 100 yards of the border are distinctly more sodic and silicic and poorer in mafics and potash than the rest of the body. The former group of rocks has been designated as the Border group. The average modal compositions of the two groups of rocks are as follows:

TABLE 1

Minerals	Border Group (13 samples)		Central Group (21 samples)	
	Volume percent	Standard deviation	Volume percent	Standard deviation
Quartz	31.8	6.65	27.9	5.70
Plagioclase	41.7	9.05	30.8	6.65
Microcline	22.1	10.12	32.8	4.04
Biotite and chlorite	3.6	2.94	5.6	3.04
Hornblende	0.3		2.2	
Magnetite	0.1		0.1	
Rest	0.4		0.6	
Average An	$An_{9.5}$		$An_{12.5}$	
Average $\frac{Kf \times 100}{\text{Total Feldspar}}$	34.6		51.6	

Since the border group represents only 15-20 percent of the total area of the pluton, a straight average of the two groups would not give the fair estimate of the average composition of the granite. Thus in computing the average composition (table 2) the central and the border groups were weighted in the ratio of 21:4 respectively.

TABLE 2

Average Composition of the Wollaston Biotite-Hornblende-Granite

	Vol. percent
Quartz	28.5
Plagioclase	32.6
Microcline	31.1
Biotite-chlorite	5.3
Hornblende	1.9
Magnetite	0.1
Rest	0.5
Average An	$An_{11.5}$
Average $\frac{Kf \times 100}{\text{Total Feldspar}}$	48.8

Chemical analysis of a sample of the central group (rather rich in plagioclase) was obtained and its observed mode and calculated norm are given below along with the chemical data (Sample W 603):

TABLE 3

	Percent	Mode	Vol. percent		Molecular Norm.
SiO_2	71.88	Quartz	30.4	q	28.6
TiO_2	0.37	Plagioclase	29.4 (86.2)	or	25.5
Al_2O_3	11.66	Microcline	26.4	ab	36.0
Fe_2O_3	1.34	Biotite	7.4	an	1.0
FeO	2.63	Hornblende	4.2	c	0.4
MnO	0.06	Calcite	1.0	hy	4.8
MgO	0.72	Magnetite	0.4	mt	1.5
CaO	1.13	Allanite	0.3	il	0.6
Na_2O	3.92	Apatite	+	ap	0.3
K_2O	4.18	Sphene	+	cc	1.4
P_2O_5	0.10	Zircon	0.5		
H_2O	0.73				
CO_2	0.57				
	99.29		100.0		100.1

Analyst: H. B. Wiik.

VARIATIONS WITHIN THE PLUTON

There are two types of systematic spatial variations in the composition of the biotite-hornblende granites in the pluton:

A. *Variations in a north-south direction*: The rock tends to become relatively more siliceous and less mafic as one proceeds from south to north. The average amounts of quartz and mafics in a series of samples collected across the southern end, the central section and the northern end of the pluton, are as follows:

TABLE 4

Biotite-Hornblende Granites

Average values

	Quartz %	Mafics %	Hornblende / Biotite	Remarks
South end (5)	20.1	6.7	0.40	Hornblende always present.
Central section (6)	29.1	6.0	0.19	Hornblende absent from border sample.
North end (5)	33.7	4.5	0.08	—do—

B. *Variations with respect to the border*: As already noted, the border group of the granite is markedly different from the central group. There are, however, all gradations between the two. As the granite border is approached, the following changes are noticed:

(1) proportions of quartz and plagioclase increase;
(2) proportion of the mafics and the ratio Kf/Pl decrease;
(3) plagioclase tends to be more sodic;

(4) ratio of hornblende to biotite decreases; often hornblende is altogether absent in the border group; this indicates that the border region of the pluton is relatively rich in water.

Most of these variations occur within 100 yards of the border, although at some localities the change begins to be noticeable about 200 yards from the border. The rates of these changes increase as the border is approached; in fact, these changes are approximately exponential with respect to distance.

The remarkable features of these variations are: (1) they are present in all parts of the pluton, (2) they are noticeable locally also against the major roof pendant in the central section of the pluton; (3) similar variations occur also with respect to the border of at least one off-shooting dyke.

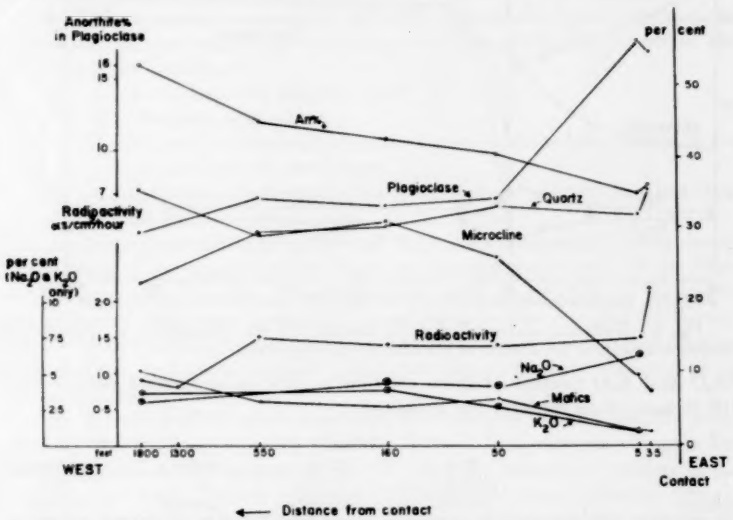

Fig. 2. Wollaston pluton: Variations in compositions with respect to its eastern border at grids 73,000 N : 72,500 E.

A suite of specimens collected at varying distances from the eastern border of the pluton along an approximate straight line near grids 73,500 N: 72,500 E were studied in detail (fig. 2). Similar changes at the border of the long dyke of granite, cutting across biotite paragneiss along the road to Rose Island were also studied in detail (fig. 3). In this case, however, the variations are confined to within 3 feet of the border. Nevertheless, the same trends of variations (except that of decreasing anorthite content towards border) are present and they are approximately exponential in nature.

Variation in composition of the country rocks adjacent to the granite border: Three samples of biotite paragneiss were collected off the western margin of the long granite dyke, near the cuts along the road to Rose Island. All these samples are approximately along strike and collected at distances of 2 feet, 5 feet, and 15 feet, respectively from the granite contact. Modal analyses,

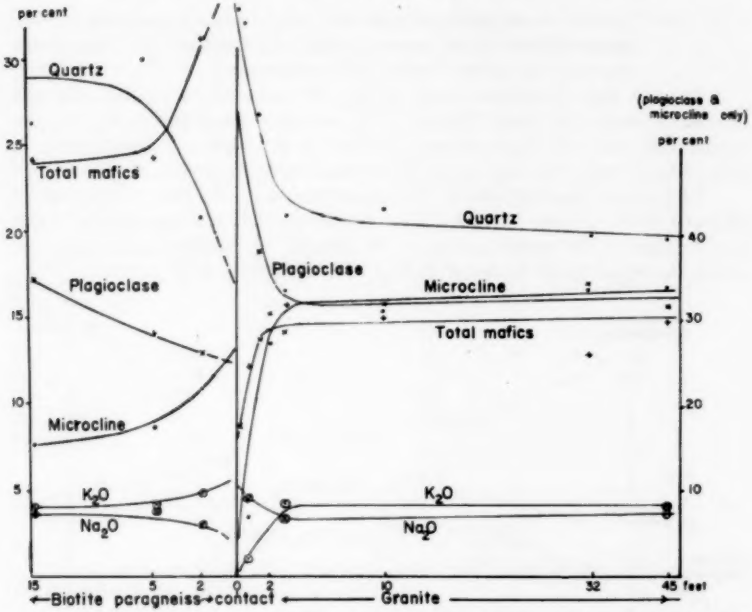

Fig. 3. Wollaston pluton: Trends of variation in the composition of granite and biotite paragneiss at the contact of the offshooting long dyke.

Na_2O and K_2O content of these samples as well as of another sample over 100 ft. away from the dyke are as follows:

TABLE 5

Samples	W 9 (100 ft.) percent	W 11 (15') percent	W 946-5 (5') percent	W 946-2 (2') percent
Quartz	30.4	26.2	30.1	20.9
Plagioclase	35.6	34.1	28.0	25.9
Microcline	1.6	15.4	17.2	21.8
Biotite	29.5	23.1	23.9	30.3
Iron Ore	0.4	1.0	0.3	0.8
Muscovite	2.4	—	—	—
Apatite and Sphene	0.1	0.2	0.5	0.3
$Na_2O\%$	3.95	3.54	3.96	3.05
$K_2O\%$	3.22	4.16	4.12	4.91

On plotting the compositional data for the three samples of biotite paragneiss (near granite contact) against distance from the granite border (fig. 3), one notices several interesting trends:

(1) while the content of quartz, plagioclase and Na_2O in granite tend to rise exponentially towards the contact, those in biotite paragneiss tend to fall;

(2) while the content of microcline, total mafics and K_2O in granite fall exponentially towards the contact, those in biotite paragneiss tend to rise;

(3) there is absolutely no gradation between the compositions of the granite and the paragneiss. In fact, the compositional contrast between them is the sharpest at the contact.

CAUSES OF THE VARIATIONS

A. *North-South Variations.*—The granite becomes more siliceous and less mafic as one proceeds from south to north. Further, the progressively lower hornblendes/biotite ratio towards the north suggests that the magma was richer in water towards the north. The south-plunging lineation in the pluton, as already referred to, is indicative of the movement of the magma from south to north. The tendency for a more acidic, quartzose and water-rich composition towards the north supports this idea.

B. *Variations with respect to the border.*—Several alternative explanations to account for the remarkable variations with respect to the border of the pluton may be considered:

1. Assimilation of country rocks
2. Marginal albitisation
3. Magmatic differentiation with intrusion of the later phases of the magma towards the border
4. Diffusion of soda and silica in an aqueous solution expelled from the heated country rocks.

1. *Assimilation*: The possibility of the border composition being due to assimilation of the country rocks cannot be considered seriously, as the latter are all more mafic or calcic than the granite itself. Assimilation of the biotite paragneiss or calcareous paragneiss would have produced a dioritic border, while that of crystalline limestone would have produced a desilicated alkaline rock. Further, inclusions of country rocks are not particularly abundant along the border zones.

2. *Marginal albitization*: Alteration of the border zones of granitic intrusives by the residual soda-rich solutions derived from the same magma has been suggested as the explanation for the relatively more sodic borders of the Bourlamaque mass, Quebec (Güssow, 1937) and the Sparta granite, Oregon (Gilluly, 1933). Textural evidences of albitization are available in both the above-mentioned cases. In the present case, however, no evidence of albitization is seen. Many of the marginal samples are aplitic in nature; in these rocks, microcline can be seen enclosing and embaying plagioclase crystals in places, but the reverse relationship is never seen.

3. *Magmatic differentiation*: The border phase might represent a later soda- and silica-rich fraction of the same magma as produced the central phase. One might assume that emplacement of progressively more sodic and silicic fractions took place around the partly crystallized rocks, as the magma was expanding outward.

This explanation does not, however, satisfactorily account for the approximately exponential nature of the variations with respect to the contact. It would appear as if some process with a distinct spatial relationship to the country rock has operated.

4. *Diffusion of soda and silica from the country rocks*: As pointed out by Kennedy (1955), when a relatively dry hot magma is intruded into cool sedi-

ments, the temperature of the sediments close to the magma rises rapidly and in consequence, the partial pressure of water in the sediments may increase at a rapid rate, provided that this water does not communicate directly with the surface of the earth. This water then escapes by diffusing into the magma. In this way the marginal portions of the melt may become greatly enriched in water and in the more soluble components from the surrounding rocks.

Water would be liberated in the country rocks also through decomposition of hydrous minerals and as a byproduct of metamorphic reactions. The diffusion process would take place only at an early stage in the crystallization of the granitic magma, when the melt may be undersaturated with respect to water (Smith, 1948).

If soda and silica are the chief constituents carried in as a result of such aqueous diffusion, the marginal region of the granite body would be richer in soda, high in silica, high in hydrous minerals and relatively poorer in the other constituents. Further, as is characteristic of all diffusion processes, the amount of the added material would fall off exponentially with distance from contact.

An attempt was made to find out how far the present data fit with the above picture. Assuming that Na_2O and SiO_2 are the only constituents added by diffusion to the sets of samples from the eastern border of the pluton (represented on fig. 2) and that the sample W200 is uncontaminated, the approximate amounts of contamination in each of the samples were estimated by fitting the values of SiO_2 (calculated from modal composition), Na_2O percent and

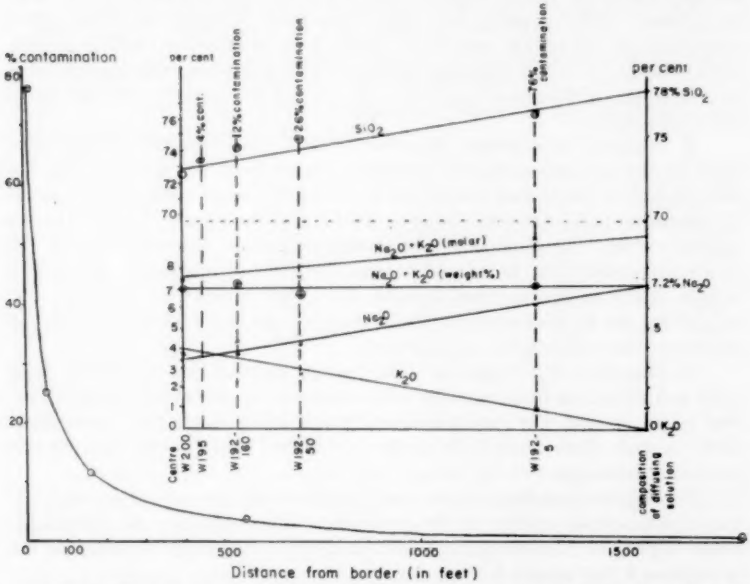

Fig. 4. Percentages of possible contamination from solutions diffusing from the wall rocks *versus* distance from border of the pluton, in samples of Wollaston granite.

K_2O percent in approximate straight lines (fig. 4). On plotting the values of contamination against distance from contact, an exponential type of curve is obtained (fig. 4). A similar curve is obtained also for the set of samples collected across the granite dyke.

Another effect of such diffusion of silica and soda would be to impoverish the country rocks at the contact in these constituents. There are, however, several difficulties in verifying this point: (1) composition of the country rock is rather variable in nature, even along strike, so that a very large number of samples would be needed in order to verify this idea; (2) the effects of such leaching might have been obliterated due to later emanations of siliceous and alkaline pegmatitic or hydrothermal fluids during the later stages of crystallization of the granite magma; and (3) suitable fresh outcrops of the country rocks at granite contacts are rare in this area.

Study of the set of samples of biotite paragneiss off the western margin of the long dyke does indicate, however, that the country rock at the granite contact tends to be poorer in plagioclase, Na_2O and quartz—precisely the same constituents in which the border region of the granite dyke is enriched; further, the compositional contrast between the granite and the paragneiss tends to be the sharpest in the immediate vicinity of the contact. This last condition would rule out any hypotheses based on a metasomatic origin of the granites in the contact region, for in that case, one would expect gradational variations. The observed trends of variation could be explained in either of the two ways, viz. (1) transfer of some constituents (chiefly K_2O and mafics) from the granite into the biotite paragneiss, or (2) transfer of certain constituents (chiefly Na_2O and SiO_2) from the paragneiss into the granite. Now, there is no textural evidence of granitic materials being introduced into any of the samples of biotite paragneiss, so that diffusion of solutions rich in Na_2O and SiO_2, leached out of the biotite paragneiss into the granite, appears to be the most probable explanation.

Recent experimental work of Tuttle (personal communication) would suggest the feasibility of aqueous diffusion of silica, alkalies and alumina under natural conditions. Tuttle carried out some experimental studies on natural granites and found "that granite will lose silica by diffusion through water vapour at 60,000 psi and 650°C at rapid rate; in fact the granite can be changed to a syenite in a few days under these conditions. In general, silica, alkalies and alumina will move rapidly under these conditions, whereas CaO, MgO and FeO will remain behind." Thus there should be no objection to such diffusion proceeding from the country rock into a liquid magma, provided the necessary chemical potential is there.

A careful search of literature for quantitative data on the variation of composition in granite bodies was made in order to find out if similar variations described from elsewhere could be explained on the basis of aqueous diffusion from country rock. It was rather surprising to find, however, that although a tremendous volume of work has been carried out on the granite problem, only rarely do such publications give quantitative data on variations of composition at *specified* distances from contact. Such data as are available are given by the protagonists of granitisation, who have often sought to estab-

lish gradation between the country rocks and the granite; in most of the examples described, the granite rock tends to become more mafic and less silicic towards the border. The only instance parallel to the present case is that described by Whitten (1957) at the Bloody Foreland granite-quartzite contact of the Donegal granite, Ireland. Whitten describes interesting variations in the contents of SiO_2, Al_2O_3, K_2O, Na_2O, (Fe, Mg)O, Fe_2O_3 and CaO (as computed from modal analyses) in a series of samples of feldspathic quartzite in contact with granite (within 4½ feet of contact). Here, although the variations of most of the constituents are gradual, SiO_2 and Na_2O are the highest and K_2O lowest in the marginal specimen of granite and also the variations tend to be the sharpest nearest the contact, as in the Wollaston pluton. Although Whitten has attributed the observed variations to granitization of the quartzite through solutions rich in alkalies, the sudden drop in the K_2O content at the border of granite has not been explained. Aqueous diffusion of Na_2O and SiO_2 from the country rock would possibly explain the facts better.

Returning to the variations in the Wollaston pluton, it would seem that the hypotheses of aqueous diffusion of Na_2O and SiO_2 into the granite fits the available facts the best. This cannot, however, be considered as firmly established, until (1) the theoretical possibility of the diffusion of aqueous solutions from the country rocks into an intruded granitic magma is verified by further laboratory experiments, and (2) more evidence of leaching out of certain constituents from the country rock has been found.

SOME REMARKS ON THE CONCEPT OF "BASIC FRONT"

The mechanism of aqueous diffusion of alkalies and silica from the contact zones of the country rocks into the granite magma, as suggested in this paper, would tend to cause basification of the country rocks and the inclusions in the magma. This tendency is distinct in biotite paragneiss at the contact of the long granite dyke, as described above (fig. 3).

Similar relatively basic contact zones of country rock and outer parts of inclusions in granitic rocks have been regarded by the "transformist" school as "basic fronts", being due to concentration of iron, magnesia and some other elements expelled from an adjacent zone of granitization (Reynolds, 1946). While the reality of such zones cannot be doubted, their petrogenic significance is uncertain. The "magmatists" have generally regarded such zones as effects of contact metasomatism between the materials emanating from the crystallizing magma and the country rocks or inclusions (Turner and Verhoogen, 1951, p. 291). More recently, some workers have suggested a process of partial melting and squeezing out of materials rich in alkalies and silica, during high grade metamorphism, as being responsible for the origin of certain typical basic front rocks (Tuominen and Mikkola, 1950).

The present study appears to indicate that aqueous diffusion of alkalies and silica from the contact zone of the country rocks could also account for the development of the so called "basic fronts". Such diffusion would proceed only as long as the magma is undersaturated with respect to water. Once the magma becomes saturated with water, due to (1) crystallization of the relatively anhydrous phases, and (2) infusion of water from the country rocks, this

process will stop and ultimately, hydrothermal and pegmatitic solutions from the crystallising magma will tend to stream out of the magma into the country rocks.

One may thus conceive of two stages of transference of materials between an intrusive magma body and the adjacent country rocks or inclusions:

(1) An early stage of basification of country rocks, accompanied by enrichment of the marginal zones of the magma in alkalies, silica and water;

(2) A later stage of acidification of the same country rocks, producing such effects as feldsapthization, silicification and hydrothermal alterations.

The later stage of acidification will tend to obliterate the effects of the earlier basification, unless in the meantime, the contact between the magma and the country rocks has been effectively sealed as a result of a more or less complete crystallization of the marginal zones of the magma, so that the basified country rocks escape the attack from the residual solutions from the magma. This would account for the relative rarity of clear examples of the so-called "basic front".

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GLACIATED PEAKS IN THE NORTHERN COAST RANGES, CALIFORNIA

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ABSTRACT. Three, and possibly four, isolated peaks in the northern Coast Ranges of California have been glaciated. Altitudes of the peaks range from 6, 873 to 7,448 feet and altitudes of cirque floors range from 6,400 to 7,000 feet. Evidence of glaciation consists primarily of rounded bedrock outcrops, striated rock surfaces, and cirque-like forms at the heads of valleys. Total area covered by glaciers probably did not exceed 3 square miles. Talus in cirques, poor preservation of striations, and erosion of moraines suggest early Wisconsin glaciation.

INTRODUCTION

The California Coast Ranges extend from north of Eureka southward to the region east of Santa Barbara. A 150-mile portion centering on San Francisco Bay has no peaks higher than 5,000 feet. In both the northern and southern portions, however, many peaks exceed an altitude of 6,000 feet and a few exceed an altitude of 7,000 feet. Locations and altitudes of principal peaks in the area studied are shown in figure 1.

The only published accounts of glaciation in the northern Coast Ranges are by Holway (1911, 1914). His first paper is a detailed account of the evidence of glaciation on Snow Mountain, but his second paper is only a short abstract which merely mentions the fact that Snow Mountain, Hull Mountain, and Black Butte have been glaciated. Little has been added to Holway's work apart from the publication of modern topographic maps which present, for the first time, an accurate picture of the distribution and altitudes of the higher peaks.

The purpose of the present paper is to review the little known work of Holway and to describe in greater detail the evidence of glaciation on Hull Mountain and Black Butte. In addition, evidence of the glaciation of Anthony Peak is presented for the first time.

CLIMATE

The northern Coast Ranges are within the area of cool, moist climate characteristic of the coastal areas of Oregon and Washington. Lines of equal temperature and precipitation generally parallel the Pacific Coast; consequently, temperatures in the northern Coast Ranges are only slightly warmer and rainfall is only slightly less than areas to the north. Unfortunately, climatic data are unavailable for the high mountains of the Coast Ranges. Some inferences can be drawn, nevertheless, from data of nearby stations and from Sierra Navada stations 90 miles to the east (table 1). The marked effects of topography can be seen by comparing precipitation figures for Upper Lake Ranger Station and Hullville. The total difference in altitude is only 578 feet, yet the precipitation difference is 14.8 inches. The rain shadow effects of topography can also be seen in the precipitation record at Fouts Springs which is in the lee of Snow Mountain. Here rainfall is lower than Upper Lake 7W despite a slightly higher elevation.

A comparison between Sierra Nevada and Coast Range stations having roughly the same altitude and latitude shows that both winter and summer tem-

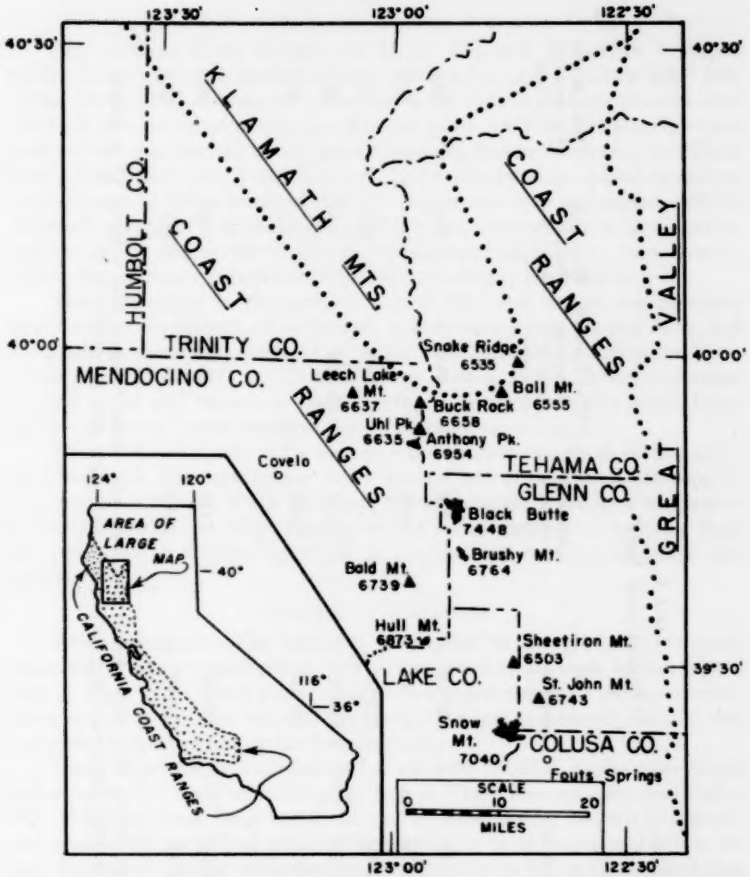

Fig. 1. Distribution of peaks higher than 6,500 feet in the northern Coast Ranges of California. Areas above 6,500 feet are shown in black; small triangles indicate peaks with small summit area. Boundaries of physiographic provinces are taken from Jenkins (1943) and are shown by dotted lines.

peratures are slightly lower in the Coast Ranges. A direct comparison of precipitation is not possible because precipitation increases rapidly with altitude, and stations of identical altitude are lacking. The precipitation at Hullville, however, is only 0.9 inch per year less than the nearest Sierra Nevada station at Colfax which is almost 500 feet higher. Thus precipitation at a given altitude and latitude in the Coast Ranges is probably as high as, or higher than, in the Sierra Nevada. These comparisons in turn suggest that, if past climatic patterns were similar to those of today, Pleistocene climates were more favorable for glaciation at a given altitude in the northern Coast Ranges than in the northern Sierra Nevada.

TABLE 1
Climatological Data*

Station	Latitude	Longitude	Altitude (feet)	Mean January Temperature (°F)	Mean July Temperature (°F)	Mean Annual Precipitation (inches)
Northern Coast Ranges						
Covelo	39°47′	123°15′	1,390	40.0	73.5	38.2
Fouts Springs	39°21′	122°40′	1,650	—	—	35.9
Hullville	39°25′	122°56′	1,925	40.7	71.3	45.5
Upper Lake RS	39°10′	122°55′	1,347	43.7	72.6	30.7
Upper Lake 7W	39°11′	123°02′	1,520	—	—	42.5
Northwestern Sierra Nevada						
Colfax	39°06′	120°58′	2,418	43.7	76.8	46.4
Grass Valley	39°12′	121°02′	2,693	44.1	76.7	52.3

*Data taken from: United States Weather Bureau, 1957, Climatological data, California: Annual Summary 1956, v. 60, no. 13, p. 384-409. United States Department of Agriculture, 1941, Climate and man: Yearbook of Agriculture 1941, p. 783-797.

TOPOGRAPHY AND BEDROCK GEOLOGY

The northern Coast Ranges are deeply dissected by narrow V-shaped valleys. Local relief commonly exceeds 1,000 feet but rarely exceeds 2,000 feet, within a horizontal distance of 5,000 feet. A few upland surfaces of small local relief are present between altitudes of 6,000 and 6,700 feet. These surfaces are most extensive in the vicinity of Bald Mountain, Brushy Mountain, and Black Butte. Both Diller (1902) and Holway (1911) also noted an upland surface on Snow Mountain. Diller assumed that this surface was once continuous with his "Klamath peneplain". Modern topographic maps, however, fail to show similar surfaces within the southern part of the Klamath Mountains; consequently, Diller's long-distance correlation is judged to be highly conjectural.

The high ridges in the northern part of the Coast Ranges are underlain by a complex assemblage of sandstones, shales, basic intrusives and flows, and low-grade metamorphic rocks, all of which have been placed within the Franciscan group of Jurassic and Cretaceous age (Irwin, 1957). Structure consists of tight folds and numerous faults having a dominant northwesterly trend which is reflected by the trends of the major valleys and ridges.

Shale and standstone in the higher peaks weather rapidly as evidenced by abundant talus, fine rock rubble, and a general lack of prominent outcrops. In contrast, greenstone on Black Butte and Snow Mountain is resistant and, where fractured, breaks into large angular blocks. Conglomerate on Anthony Peak has resistance to weathering which is intermediate between sandstone and greenstone.

EVIDENCE OF GLACIATION

Snow Mountain.—The following description of the glaciation of Snow Mountain is taken from Holway (1911). Inasmuch as his work is documented with pictures and a block model which corresponds closely to the topographic detail shown on the new maps of the area, it was not considered essential that this peak be checked during my reconnaissance.

Snow Mountain is a sprawling feature with abudant north-facing slopes and a number of small north-trending valleys. These features combined with a high elevation favor large accumulations of snow during the winter months and favored the growth of small valley glaciers or large cirque glaciers in the past. Under present-day conditions, snow often persists into midsummer. Large patches of snow were seen from a distance of 24 miles during the last week in June, 1957.

Two areas have been glaciated. One is at the head of a deep north-trending valley on the northwestern corner of the mountain. The other is on the north-facing slope of an open valley on the eastern side of the mountain. The highest cirque floor has an altitude of about 6,700 feet, and the lowest about 6,500 feet. The largest ice mass was in the eastern valley and was about 1½ miles long and had a maximum width of ¾ mile. This glacier descended to an altitude of 5,950 feet which presumably is the lowest glaciated point on the mountain. Total area covered by the two glaciers must have been about one square mile.

From Holway's description, one gathers that considerable postglacial weathering and erosion have taken place on Snow Mountain. Striations are

poorly preserved, moraines are dissected, and slide rock has partly filled the small cirques.

Black Butte.—Black Butte, with an altitude of 7,448 feet, is the highest peak in the northern Coast Ranges. The small summit area, however, is oriented in a north-south direction leaving a minimum number of north-facing slopes favorable for snow accumulation. Only four small patches of snow were present on the northern and northeastern slopes during the last week of June, 1957. These were gone one month later.

Unmistakable signs of glaciation are confined to a small valley within Snow Basin on the northeastern slope of the peak (fig. 2). The valley has a step-like floor containing rounded outcrops of bedrock, perched boulders, and a few poorly preserved striations on bedrock. Deposits of unsorted rocks, sand, and silt are also at the lower end of the valley. Soil profiles developed in these deposits are youthful, probably due in part to erosion. The B horizons are poorly defined, having little clay accumulation and only a slightly redder hue (10YR, dry) than the hue of the parent material (2.5 Y, dry). The position of the deposits within the lower part of the valley and their ridge-like forms strongly suggest that they are dissected moraines. The lack of rock rubble on the higher treds of the bedrock steps makes a landslide origin unlikely as an alternative explanation. In addition to the foregoing evidences of glaciation, Snow Basin has a general theatre shape as well as a small, vertical rock wall about 150 feet high in the southeastern part. A well-defined cirque, nevertheless, has not been formed; or if once formed, it has been strongly modified by erosion.

The valley which contains positive evidence of glaciation has an area of only ⅛ square mile. The following three lines of evidence, however, suggest that a much larger area has been glaciated (fig. 2): (1) The western side of Snow Basin has numerous rounded bedrock outcrops similar to those formed by glacial erosion. (2) Youthful soil profiles are present on relatively flat areas in Snow Basin and Plaskett Meadows, indicating a recent period of erosion by an agent other than streams. (3) A small moraine-like hill composed of unstratified sand, silt, and gravel has blocked the drainage of Plaskett Meadows and has formed a small lake.[1] Slopes adjacent to the lake are not steep, so a landslide origin of the moraine-like material is unlikely. The weakest aspect of the foregoing interpretation lies in the fact that a small valley cut by Snow Basin Creek separates Snow Basin from Plaskett Meadows. Thus under present conditions, a glacier would be deflected down the present valley of Snow Basin Creek rather than terminating in Plaskett Meadows as shown in figure 2. The valley is, however, narrow and is mostly cut in soft shale. These features indicate that the valley is geologically recent, having probably been formed after the area was glaciated.

Anthony Peak.—Although Anthony Peak is higher than Hull Mountain and almost as high as Snow Mountain, Holway (1914) did not list it as one of the glaciated peaks of the Coast Ranges. Nevertheless, glaciation of the peak is strongly suggested by (1) the cirque-like form of the northern side of the peak, (2) large winter accumulations of snow which often persist into mid-

[1] The present lake is an artificial enlargement of the original lake shown in figure 2.

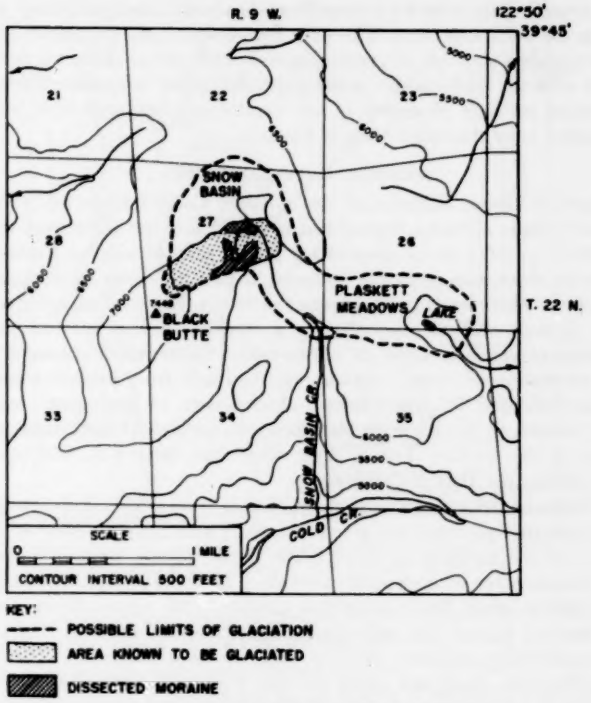

Fig. 2. Glaciated area on Black Butte.

summer, and (3) rounded exposures of graywacke on the northern part of the cirque floor. The surface of the rounded exposures are, however, weathered and show no striations.

Several small landslide masses partially fill the southern part of the cirque. Also, bedrock at the crest of the mountain has a large fracture produced by incipient landslide movement. These facts might suggest that the theatre-shaped depression is not a cirque but was made by landslide movement. Nevertheless, the small size of the slides and the absence of landslide debris on the northern part of the cirque floor as well as downslope from the cirque indicate that the slides were too small to account for the origin of the cirque.

The area of the glacier could not have been larger than ¼ square mile and was probably about ⅕ square mile. The lowest altitude reached by the glacier was about 6,300 feet, and the altitude of the cirque floor is about 6,450 feet.

Hull Mountain.—Hull Mountain was mentioned by Holway (1914) as a glaciated peak. He did not, however, cite evidence for his conclusion. Hull Mountain was visited briefly during this study, but the northern slope was not thoroughly traversed on foot. The northern slope does have a shallow theatre

shape; nevertheless, it lacks a prominent headwall. Also, striations were not found on the rock exposures. The only features strongly suggestive of glaciation are rounded outcrops of graywacke with little soil or sliderock cover. This contrasts with the thick mantle on the south side of the mountain. The evidence of glaciation on Hull Mountain is not convincing; although final judgement must await a more thorough study of the area.

REGIONAL CIRQUE ALTITUDES

Observed cirque altitudes of the northern Coast Ranges are 400 to 600 feet below cirque altitudes determined by projecting the form lines shown by Flint (1957, p. 309) in his generalized glacial map of western United States. In order to check this apparent anomaly, it was necessary to compile a new map of cirque altitudes in northwestern California. Regional mapping of cirque altitudes is made difficult, however, by a complete lack of modern published descriptions of glaciated areas in northwestern California. Fortunately, a reasonable estimation of cirque altitudes can be made from modern topographic maps supplemented by unpublished observations of geologists[2] who have mapped bedrock in the Klamath Mountains. In addition, I have made a reconnaissance of the western Trinity Alps which has helped to establish cirque altitudes within the Helena Quadrangle.

Altitudes of the lowest cirque floors within several 15-minute quadrangles in northwestern California are given in table 2 and figure 3. Most of the altitudes are of the surfaces of small lakes which occupy cirques. Lakes were chosen because maps with contour intervals of 80 and 100 feet show insufficient detail to define small flat areas which constitute the cirque floors. Only one lake is listed as a guide for each quadrangle; nevertheless, other cirque floors having equally low altitudes exist in each of the quadrangles. The average altitudes of cirque floors are about 200 feet higher than the lowest cirques in areas of slight glaciation and about 400 feet higher than the lowest cirques in the heavily glaciated Trinity Alps.

Altitudes of cirques in the northern Coast Ranges appear to be compatible with those of the southern Klamath Mountains as shown in figure 3. However, the sharp bend in the 6,500-foot form line just north of latitude 40° may represent a slight anomaly. Field work is needed in this area in order to establish better the altitudes of cirque floors which do not contain lakes.

Figure 3 immediately suggests that many glaciated peaks exist outside of those shown on the Glacial Map of North America (Flint and others, 1945). The part of the Klamath Mountains south of the Trinity River is of particular interest in this regard. Within this area, there are at least 6 major peaks with altitudes of more than 7,000 feet. Topographic maps of all of these peaks show well-developed cirque-like forms on the northern slopes. With the exception of brief mention of glaciation on the Yolla Bolly Mountains by Diller (1902, p. 58), these features have not been described in the published literature.

AGE OF GLACIATION

Correlations of glacial events in the Cordilleran region have been based almost entirely on the relative extent of various glacial advances, amount of

[2] Names are listed in the acknowledgments.

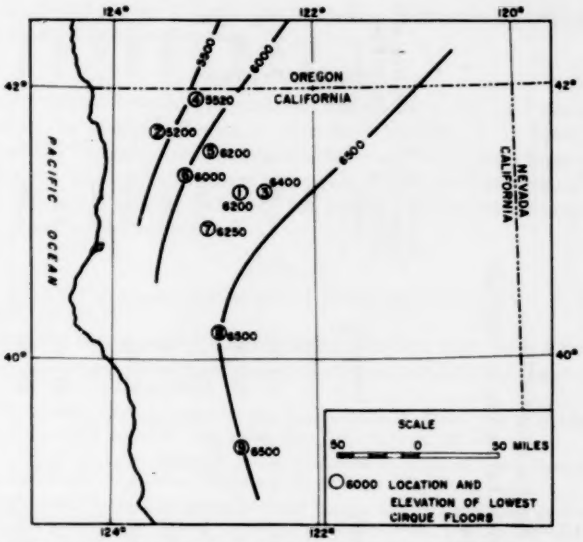

Fig. 3. Form lines showing the minimum altitude of cirque floors in northwestern California. Numbers within circles correspond with numbers in table 2.

erosion of glacially formed features, and the degree of weathering (Flint, 1957, p. 328-330). The extent of various glacial advances cannot be used in the Coast Ranges because only one advance has been recognized. Furthermore, two important reasons make the use of the degree of weathering quite difficult. (1) The closest modern studies of glaciation have been in the central Sierra Nevada, a distance of some 200 miles. Differences in climate and bedrock within this distance are significant. (2) Sierran glaciers were large enough during each period of expansion to erode all weathered and partly weathered bedrock and to leave exposures of fresh bedrock within the glaciated area. In contrast, glaciers in the Coast Ranges were feeble and freshly glaciated areas must have contained patches of partly weathered bedrock.

Evidence relating to the age of glaciation in the Coast Ranges is largely based on the degree of erosion and soil development within the glaciated areas. The moraines on both Black Butte and Snow Mountain have been breached by small streams, and their surfaces have been eroded by local runoff so that the morainal forms are partly erased. Most of the cirques are partly filled with slide rock and small landslides. Striations are only poorly preserved on resistant greenstone, and striations have not been found in the graywacke, shale, or conglomerate. These facts suggest that glaciation antedates late Wisconsin glaciation which is widespread in the higher mountains of the Cordilleran region. On the other hand, the fact that soil profiles in glacially transported material are in a youthful stage of development and also the fact that many topographic features, though modified by erosion, are still recog-

TABLE 2

Altitudes of Lowest Cirque Lakes in Northwestern California
(Altitudes are estimated from topographic maps having contour intervals of 80 and 100 feet)

USGS Topographic Map (15-minute series)	Reference Area of Cirque Floor	Latitude	Longitude	Altitude of Highest Peak in Vicinity (feet)	Altitude of Cirque Floor (feet)
1. Bonanza King	Little Bear Lake	41°12′	122°43′	7,006	6,200
2. Dillon Mountain	Area south of Bear Lake	41°42′	123°35′	5,740	5,200
3. Dunsmuir	Upper Cliff Lake	41°12′	122°30′	7,149	6,400
4. Seiad Valley	Elk Lake	41°56′	123°10′	6,700	5,520
5. Scott Bar	Man Eaten Lake	41°31′	123°08′	7,646	6,200
6. Forks of the Salmon	Lily Lake	41°23′	123°16′	6,873	6,000
7. Helena	Upper Boulder Lake	40°57′	123°03′	8,200	6,250
8. Yolla Bolly	North Yolla Bolly Lake	40°12′	122°58′	7,863	6,500
9. Stonyford	Area C of Holway, 1911	39°22.5′	122°45′	6,898	6,500

nizable as glacial forms indicate that an early Wisconsin glaciation of the northern Coast Ranges is probable.

ACKNOWLEDGMENTS

I have gained valuable information about the extent and character of glaciation in the Klamath Mountains from D. B. Tatlock, W. P. Pratt, and W. P. Irwin of the United States Geological Survey and D. P. Cox, former graduate student of Stanford University now with Anaconda Company. Professor A. D. Howard of Stanford University has kindly read the manuscript and has offered several helpful suggestions.

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GEOLOGY OF THE CENTRAL SIERRA PELONA, LOS ANGELES COUNTY, CALIFORNIA*

WILLIAM R. MUEHLBERGER and H. STANTON HILL

ABSTRACT. The central Sierra Pelona lies about 35 miles north of the Los Angeles civic center. Exposed in the map area is the thickest known section, nearly 7500 feet, of the Precambrian(?) Pelona schist.

Most of the exposed sequence consists of three types of schist in nearly equal amounts. Actinolite-chlorite schist is distinct from and does not intergrade with either the muscovite schist or its variant, the chlorite-muscovite schist. The mappable units, which total only a few hundred feet of section, are thin interbedded quartzite and marble units. A few dikes of talc schist, talc-actinolite schist, and talc-serpentine schist are present.

Chemical data derived from petrographic studies suggest that both the muscovite schist and chlorite-muscovite schist were originally sedimentary material with the composition of graywacke. The actinolite-chlorite schists resemble spilites in composition. The quartzites and marbles are clearly of sedimentary origin. This suite of rocks suggests a eugeosynclinal deposit.

The age of the Pelona schist has not been determined, although suggestive evidence indicates it is probably Precambrian.

The major structural feature of the area is a southwestward-plunging asymmetrical anticline with a smaller fold developed along the oversteepened south flank. Foliation is parallel to bedding except on minor folds where it lies parallel to the axial plane of the fold. The prominent lineations, axes of drag folds in the quartzite-marble units, and crinkling of the foliation plane in the schists plunge southwestward at angles generally steeper than the plunge of the main fold axis of the range. A second, poorly developed lineation is formed by a crinkling of the foliation and plunges down the dip of the foliation planes.

INTRODUCTION

Geologists in recent years have turned to "basement rock" studies in attempts to unravel major structural problems. One of the "basement units" that has been used along the San Andreas fault is the Pelona schist. The purpose of this paper is to place in the record data from the Sierra Pelona, the type region of the Pelona schist. Exposed in the central Sierra Pelona in Bouquet Canyon is the thickest known stratigraphic section that has a minimum of structural deformation.

The Sierra Pelona lies within the Transverse Range Province of Southern California about 35 miles north of the Los Angeles civic center (fig. 1). This range trends east-west and is about 20 miles long and 4 miles wide; it is bounded on the south by the Soledad basin, on the northeast by the San Andreas fault, and on the north and west by the Bouquet Canyon-Bee Canyon faults. Figure 2 shows the geology of about 25 square miles in the central portion of the range.

PREVIOUS WORK

William P. Blake, probably the first geologist to work in Southern California, described the schists of Sierra Pelona in 1853 while a member of Lt. Williamson's party surveying routes for the railroad from the Mississippi River to the Pacific coast (Blake, 1857, p. 59-60). He compared them to the auriferous slates of the Mother Lode and to those in the gold districts of North Carolina.

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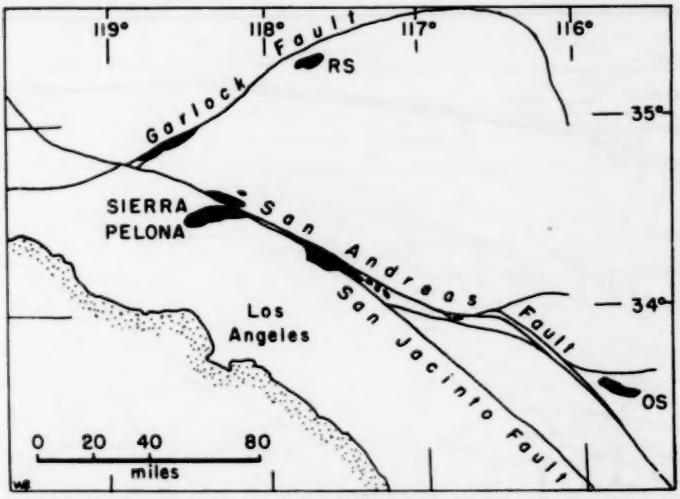


Fig. 1. Map of a portion of southern California showing major faults and location of outcrop areas of Pelona schist (unlabeled black areas) and its correlatives, the Rand schist (RS) and the Orocopia schist (OS).

The designation "Pelona schists" was first introduced in the literature by O. H. Hershey (1902a). Later in the same year he published a general description of the "Pelona schist series", based on reconnaissance work, in which he divided the schists of the type locality, the Sierra Pelona, into two main groups. One of these groups was a "uniformly light yellowish, coarse, granular mica schist of muscovite and quartz—the estimated exposed thickness is 2000 feet." He also recognized a second, or upper, schist which was dominantly dark and "seems to be a chlorite schist." He estimated this to be 3000 feet thick, thus "making 5000 feet for the series—the Pelona schist series" (1902b, p. 276). It is now known that his "upper schist" is topographically higher where he observed it but is stratigraphically lower.

Pelona schist appears in several other widely separated areas of Southern California, including Portal Ridge (Johnson, 1911; Simpson, 1934; Wallace, 1949), the eastern San Gabriel Mountains along the south side of the San Andreas fault from Valyermo to San Bernardino (Noble, 1933, p. 11-12; 1954, p. 42-43), and an elongate area between the branches of the Garlock fault in the Tehachapi Mountains (Wiese, 1950, p. 12-15). All of the above areas lie in a zone that extends for 80 miles along the San Andreas fault and is within 20 miles of the fault zone.

The Rand schist (Hulin, 1925, p. 23-31; Simpson, 1934, p. 380-381), which is identical in lithology and structure and is thus believed to be a correlative of the Pelona schist, is exposed near Randsburg, 60 miles northeast of the Sierra Pelona. Miller (1944, p. 21; 1946, p. 528) and Hill and Dibblee (1953, p. 450-451) have suggested that the Orocopia schist, which is exposed in the vicinity of the Salton Sea 160 miles southeast of the Sierra Pelona, is a

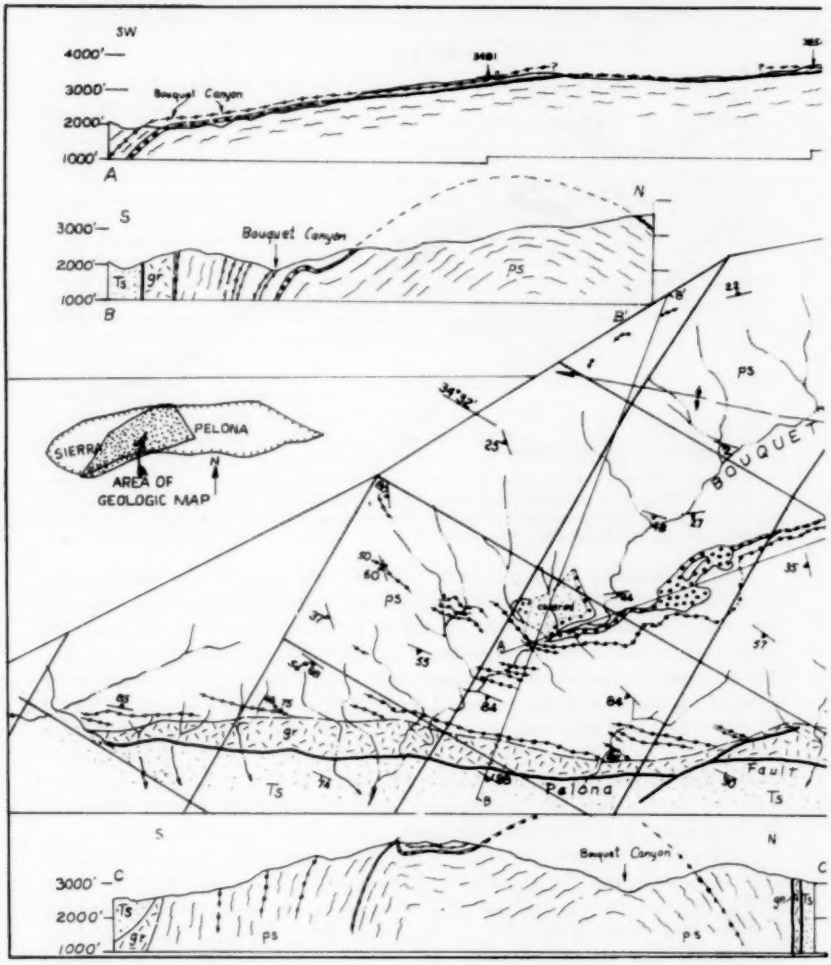
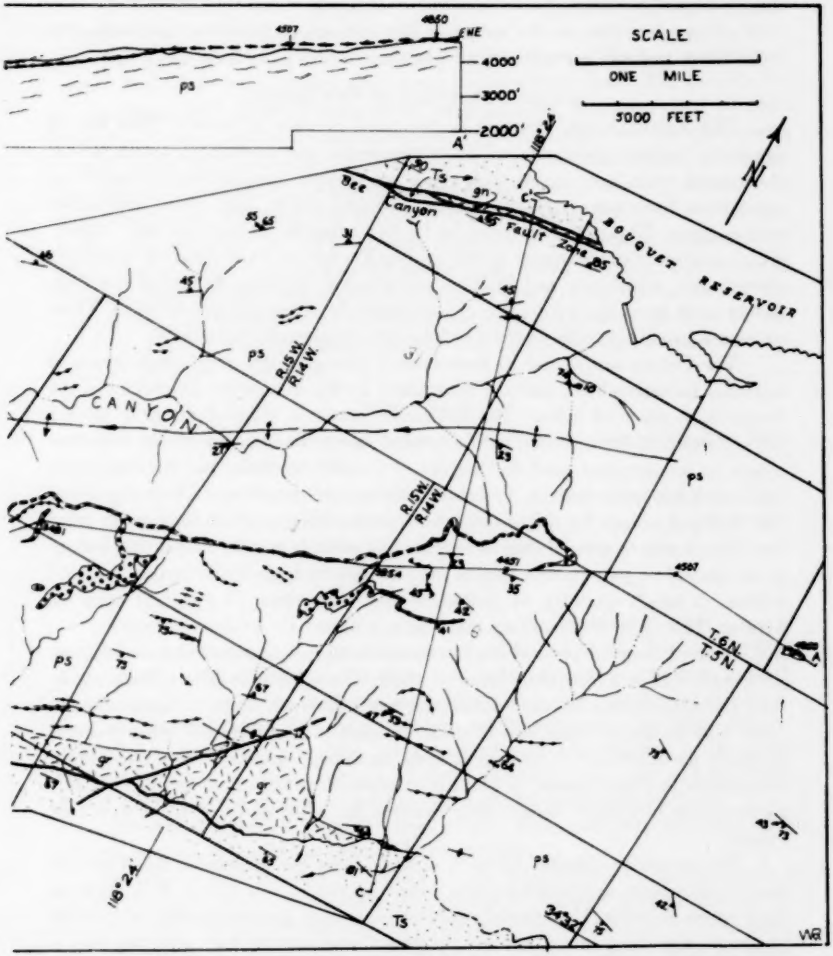


Fig. 2. Geologic map and cross-sections of the central Sierra Pelona, Los Angeles County, California. See figure 1 for location of the Sierra Pelona. Base map from U. S. G. S. 6′ Humphreys, San Francisquito and Bouquet Canyon quadrangles. Only drainage and land net shown. Symbols: ps—undivided Pelona schist, dotted area—thick interbedded marble and quartzite unit, dotted lines—thin interbedded quartzite and sub-

correlative of the Pelona schist. Schists that are texturally and mineralogically similar to the Pelona schist form the "basement" rock of the Old Puente oil field in the eastern Los Angeles basin and have led Schoellhamer and Wood-



ordinate marble; gr—intrusive igneous rocks (range in composition from granite to quartz diorite); gn—gneissic rocks; Ts—Tertiary sedimentary rocks. All Quaternary units omitted. Standard U. S. G. S. map symbols used. South-southwest-plunging minor fold axes in quartzite-marble units not shown. Lineations shown are crinkles of foliation planes. See text for further discussion.

ford (1951, map sheet) to suggest that "the Catalina and Pelona schists may grade into one another, and may be of the same age, possible pre-Cambrian". (A distinctive feature of the Catalina schist is the presence of glaucophane

and lawsonite, notably absent from the Pelona schist and its correlatives.) The lack of complete data on the metamorphic terranes of Southern California prevents more positive correlations at this time.

GENERAL FEATURES OF THE SCHIST

The Pelona schist exposed in this area consists of nearly 7500 feet of regularly bedded muscovite, chlorite-muscovite, and actinolite-chlorite schist. Associated with these major rock types are several hundred feet of quartzite, crystalline limestone, actinolite schist, chlorite schist, talc schist, and other minor types. The series appears to be conformable except for talc "dikes" which transect the schistosity at low angles. Except for local areas of subsidiary disturbance, schistosity and bedding are parallel. Igneous intrusions are rare, but in most areas the schists are accompanied by numerous quartz veins. These veins are usually parallel to the bedding but occasionally cut across.

The Pelona schist and its correlatives belong in the greenschist facies of regional metamorphism and are recognized by the distinctive lithologies of the three main types of schist. The muscovite schist is either light gray with a silvery sheen or light brown with a golden sheen. The texture varies from medium- to fine-grained, and the fissility is usually excellent, but poor in specimens with low mica content. The chief minerals are quartz and albite-oligoclase. The feldspar occurs for the most part as porphyroblasts which may range from less than 1 mm to several mm in length. The mica is usually muscovite, but up to 10 percent or more brown biotite may be observed, generally in the "golden" schists. A small quantity of green chlorite (less than 10 percent) may be present. This type weathers to a rusty brown color.

If more than 10 percent green chlorite is found in a muscovite schist, we arbitrarily call it a chlorite-muscovite schist. The color is usually a darker gray than the muscovite schist and sometimes has a greenish tinge. Occasionally the color may be almost black due to small amounts of graphite. The main mineral is albite or oligoclase in porphyroblasts as above; quartz is less important; clinozoisite is often present in grayish or greenish prismatic or tabular crystals up to a few mm long. Weathering changes the color of these rocks to a rust brown.

The actinolite-chlorite schist is distinct from the muscovite and chlorite-muscovite schists and nowhere was found to grade into either. It is light to dark green in color. Untwinned albite or oligoclase porphyroblasts, ellipsoidal in shape, are conspicuous against the green background and give the rock a mottled appearance, especially when large (5 to 6 mm). Locally the feldspar may make up 75 percent of the rock. Prismatic or tabular, greasy crystals of gray-green or greenish clinozoisite are also usually present, appearing as porphyroblasts as much as 1 cm in length. The chlorite is in dark green folia, and with the aid of a hand lens tiny, light- to emerald-green needles of actinolite can be seen. Accessory minerals are green epidote, pyrite, and limonite pseudomorphous after pyrite. These schists are coarser-grained than the muscovite schist and weather to a redder brown. Other distinctive but rare Pelona schist types are coarse actinolite schist, actinolite-talc and talc-actinolite schist,

and schist bearing the conspicuous red manganese minerals, piedmontite and alurgite.

The main structural feature of the central Sierra Pelona is a relatively simple antincline with steeper dips along the southern flank. The boundaries of the range and of the Pelona schist itself are, for the most part, all fault contacts. Along a portion of the southwestern part Tertiary sedimentary rocks overlap older faulted boundaries. The boundary between the Pelona schist and the adjacent gneiss along the southern face of the Sierra Pelona is probably an intrusive contact that later was faulted and mylonitized. The evidence for this is the local abundance of small crystals of garnet, and a general coarsening of grain size near the contact, and the presence of blocks of schist that resemble Pelona schist incorporated within the gneiss. The gradational nature of the contact and poor exposures in this region obscure the relations. Wallace (1949, p. 787) observed similar features farther east along the same contact and arrived at the same conclusion.

PETROGRAPHY

For discussion purposes the rocks of the Bouquet Canyon section have been arranged into five groups:

Muscovite schist
Chlorite-muscovite schist
Chlorite-actinolite schist
Quartzite and marble
Minor rock types

Muscovite schist.—The main rock type in the Bouquet Canyon area is muscovite schist, (table 1) probably about 3000 feet thick. The beds range from a fraction of an inch to several inches in thickness with rare beds as thick as one foot. At a distance the schist looks like interbedded sandstone and shale, the "sandstone" being the more massive schist with poor fissility and the "shale" being the thinly bedded, more fissile types. The bedding of the more massive varieties is visible because of slight differences in color. All the rocks in the group have a silvery or golden sheen on the schistosity surfaces.

The schists grouped here are those whose flaky minerals are micas and whose chlorite content is less than 10 percent (table 2).

In thin section the texture is seen to be crystalloblastic, sutured granoblastic to lepidoblastic. From 40 to 70 percent of the rock is oligoclase occurring as 1 to 3 mm subhedral and anhedral porphyroblasts, cloudy with inclusions of quartz, muscovite, and other material, usually without albite twinning striations but occasionally with Carlsbad twinning. In non-porphyroblastic types the oligoclase averages 0.1 to 0.5 mm in diameter.

Colorless muscovite in small flakes less than 1 mm average diameter lie sub-parallel with the foliation. These flakes are found bent around the porphyroblasts. It is present to the extent of 10 to 25 percent of the rock.

The quartz grains average only about 0.1 mm, frequently occurring in little patches or concentrated in single lenses perhaps 2 mm thick and 10 mm long. It has undulatory extinction, frequently possesses trains of bubble inclusions, and is present in quantities from 10 to 30 percent of the rock.

TABLE 1

Thickness in feet	Rock Description
325	Mixed rock along contact with leucotonalite; transitional types from leucotonalite to quartz-oligoclase-pennine schist.
2300	Muscovite schist, with a few thin quartzite beds.
725	Muscovite schist and chlorite-actinolite schist; thin dike of talcose rock near base.
925	Muscovite schist interlayered with chlorite-actinolite schist; quartzite and marble common; muscovite schist contains abundant chlorite in lower one-third of unit.
1975	Muscovite schist and chlorite-muscovite schist.
750	Chlorite-actinolite schist.
225	Chlorite-muscovite schist.
200	Chlorite-actinolite schist; some chlorite-muscovite schist.
	— — — — — — Base of exposed section — — — — —
7425	Total exposed section

Stratigraphic sequence of Pelona schist exposed in Bouquet Canyon. Thicknesses obtained by graphical methods, measured generally northward from the southeast corner of Sec. 16, T. 5 N., R. 15 W. along lower Bouquet Canyon. Section B-B', Figure 2, approximates an average position along the measured zones. The thicknesses given are approximate outcrop thicknesses of the schist and do not necessarily indicate thicknesses of the original depositional sequence.

TABLE 2

Mineral	Muscovite Schist	Chlorite-Muscovite Schist	Chlorite-Actinolite Schist
Albite-oligoclase	—	41	44
Oligoclase	55	—	—
Muscovite	17	17	—
Biotite	3	—	—
Chlorite	2	15	18
Clinozoisite	3	7	11
Actinolite	—	—	18
Quartz	14	15	—
Epidote	—	—	4
Calcite	—	—	2
Others	6(a)	1(b)	3(c)

(a) Calcite, magnetite, epidote, pyrite, sphene, other opaques.
(b) Epidote, graphite, sphene, magnetite, garnet.
(c) Pyrite, chalcopyrite, limonite, quartz.

Average mineral composition of the principal rock types of Pelona schist. Based on traverse collected along Bouquet Canyon in same are indicated in Figure 3.

Minor amounts of small (1 mm) brown biotite flakes are sometimes conspicuous in the planes of schistosity against a background of silvery muscovite and grayish feldspar. The biotite is elongated and in sub-parallel position in the plane of schistosity.

Other minerals present include green pleochroic pennine; interstitial and crack-filling calcite; magnetite; cloudy epidote; traces of colorless clinozoisite in broken prisms with ultra-blue interference colors or as fine, 1 mm greenish

needles; colorless subhedral garnet sometimes slightly anisotropic; pyrite cubes altering to limonite; and red hematite. A small amount of colorless, anhedral, high-relief epidote, subhedral cracked crystals of sphene and graphite may also be present.

Chlorite-muscovite schist.—The presence of more than 10 percent chlorite is arbitrarily used to distinguish chlorite-muscovite schist from muscovite schist, although all gradations between the two groups may be found. Chlorite-muscovite schist is present mainly in the middle and lower part of the Bouquet Canyon section and makes up an estimated 1500 feet of the column. These schists are frequently graphitic and are nearly always thin-bedded. Mineralogically the principal differences are an increase in chlorite with a decrease in plagioclase in both quantity and anorthite content. In thin section the texture is typically crystalloblastic with well developed schistosity.

The main mineral (table 2), constituting one-third to one-half the rock, is unstriated plagioclase, probably albite, that has a bluish cast. The anhedral, oval-shaped porphyroblasts may be elongated in the plane of schistosity and range in length from 3 to 5 mm.

Muscovite and green chlorite (pennine in part) form sinuous trains of flakes around individual porphyroblasts or groups of porphyroblasts. The chlorite is green in ordinary light and has abnormal brown interference colors under crossed nicols. The long, transversely broken and segmented clinozoisite crystals possess the usual abnormal blue interference colors and lie in the plane of schistosity.

The dark color in some specimens is due to contained graphite, an increase of chlorite, or both. The quartz and feldspar are in places almost black due to included or interstitial graphite. The quartz is usually in small (less than 0.2 mm) anhedral crystals grouped together in certain beds. Euhedral to subhedral, colorless, cracked garnets, 0.2 to 0.4 mm in diameter, are scattered throughout. Accessories are sphene, actinolite, magnetite, and limonite.

Chlorite-actinolite schist.—The chlorite-actinolite schist is distinct from the two schist groups already described. The variations in composition are minor, but grain size varies widely. The color is usually a dark green against which the white plagioclase porphyroblasts stand out distinctly, often as knots. Chlorite-actinolite schist is exposed mainly in the lower part of the section in Bouquet Canyon, where a continuous series of similar beds approaches 1800 feet in thickness.

Beds of chlorite-actinolite schist ranging in thickness from 5 to 6 feet to 25 feet or more are present in the muscovite and muscovite-chlorite schists. In one place a four-inch bed of quartzite was observed between two thick beds of chlorite-actinolite schist. In all cases the contacts appear to be conformable; many are sharp. These schists often appear to be bedded, with the feldspar porphyroblasts aligned in rough planes.

The chlorite-actinolite schist ranges in texture from coarse, dark green, chloritic, knotted schists with rough schistosity, including a noticeable linear element and marked porphyroblastic texture, to much finer, dark green, well foliated schists.

Subhedral and rounded anhedral crystals of unstriated plagioclase (albite-oligoclase) averaging 2 mm in diameter, with a maximum of 6 mm, form light

gray porphyroblasts (table 2). Many of these porphyroblasts have inclusions of clinozoisite in crystals from one-fourth to one-half the size of the poikilitic host. Fine needles of actinolite may also occasionally be seen in the feldspar. Under the microscope the large feldspar porphyroblasts are seen to be unstriated albite or oligoclase, usually cloudy, with inclusions often arranged in wavy lines parallel to the schistosity. In addition to the clinozoisite and actinolite, inclusions of blebs of quartz, small rod-shaped grains of clinozoisite(?), and subhedral apatite are found. Clinozoisite also occurs as porphyroblasts 2 to 3 mm in average length, although they may be as much as 5 mm long. These are usually longer than the plagioclase porphyroblasts and are colorless to grayish, cloudy, and in elongated broken crystals.

The groundmass is composed of dark green chlorite, light emerald green actinolite in tiny needles, and tiny elongated anhedrons of plagioclase. The chlorite and actinolite often bend around the feldspar porphyroblasts, and on occasions are sheaf-like. The green, strongly pleochroic chlorite is in strips parallel to the schistosity and, like the actinolite, often bends around the porphyroblasts to form radiating sheafs. Ripidolite, pennine, and clinochlore are present. The chlorite has either abnormal blue or abnormal brown interference colors with the ultra-blue being optically negative and the brown being positive.

Actinolite appears to be parallel to the schistosity plane, but the needles are not always parallel within that plane. They average about 0.2 mm long. Its pleochroic formula is X= very pale yellow; Y = green; Z = blue-green. Elongation is positive, with $Z \wedge C = 16°$. Refractive indices indicate about 40 percent ferrotremolite molecule in the actinolite (Winchell, 1933, p. 246).

Although normally absent, small quantities of muscovite may be present. In addition greenish epidote, pyrite, chalcopyrite, limonite, and quartz are found in trace amounts.

Quartzite and marble.—Quartzite and marble, although quantitatively minor parts of the section, are the only mappable units within the Pelona schist. The quartzite beds, 2 to 10 feet thick, are composed of individual layers of nearly pure quartzite that are less than one inch thick and separated by thin, gray-green, micaceous, calcareous laminae. The more continuous, and therefore more easily traced, beds are indicated on figure 2.

In thin section the quartzites are about 85 percent quartz with sutured outlines, numerous bubble inclusions, and undulatory extinction. Many prismatic sections are parallel to bedding (section cut perpendicular to bedding). No relict structures were observed, although Wiese (1950, p. 12) reports faint cross-bedding in the Neenach quadrangle. The remainder of the rock is calcite in anhedral crystals and interstitial fillings between quartz grains. Twinning is common, and the twinning lamellae are often bent. Both the quartz and calcite grains average 0.2 mm in diameter. Trains of muscovite flakes may be present along bedding planes. An even smaller amount of pleochroic greenish to light brown biotite is observed.

The marble is bluish-gray in beds that range in thickness from one-quarter of an inch to several feet. These are separated by quartzite beds less than one inch thick. In places actinolite-chlorite schist units 1 to 5 feet thick

separate parts of the main marble unit. The interbedded marble and quartzite are so intricately contorted that stratigraphic thicknesses cannot be determined, even where the outcrop thickness is nearly 100 feet. The marble invariably is interbedded with quartzite, and in places also with actinolite-chlorite schist. The main marble unit is indicated on the geologic map (fig. 2) by the polka-dot area. The thickest of the marble beds are consistently the most highly contorted. Scattered grains of quartz occur in the marble beds, and graphite may be present in small amounts. The quartzite beds are cemented with calcite.

Microscopically the marble is 98 percent calcite in anhedral crystals 1 to 3 mm in diameter. Twinning and cleavage lines are often bent. There is a tendency for the cleavage and twinning rhombs to have parallel orientation, the bisectors of the acute angles being sub-parallel to the plane of schistosity. The schistosity planes are outlined by stringers of quartz (average size 0.2 mm) and pale green pennine with ultra-blue interference colors. Occasional subhedral garnet, greenish epidote, and flakes of muscovite are scattered throughout.

Quartzite and marble are extremely rare in the lower one-third of the exposed schist section. The interbedded quartzite and marble sequences are common near the base of the upper member of the Pelona schist and, in fact, form the basis for subdivision. Thin quartzite beds in the upper member were traced laterally as far as they cropped out.

Minor rock types.—A few dikes of talc schist, talc-actinolite schist, and talc-serpentine schist are present in the section. These are slightly discordant with respect to the foliation of the host schists and are lenticular or ovoid bodies a few to several tens of feet in maximum dimensions. A small amount of the talc has been mined, but the lenticular nature and limited size of the talc concentrations have prevented commercial exploitation. These bodies are probably altered ultra-basic dikes.

Masses of quartz are common and range from veins a fraction of an inch thick and a few feet long to massive bodies ten feet thick and several hundred feet long. They commonly lie parallel to the foliation of the host rocks, although some transect the foliation at low angles. Some of the larger masses contain minor amounts of manganese oxides found as stains on fracture surfaces or as interstitial fillings.

ORIGIN

Table 3 presents the approximate chemical composition of the major rock types in the Pelona schist as compared to the composition of an average graywacke, average shale, and average spilite.

The muscovite schist and chlorite-muscovite schist are similar to graywackes in composition. The dominance of soda over potash in all three types of schist is significant. Other sedimentary rock types (e.g., average shale, col. 4, table 3) show a dominance of potash over soda. The absence of any relict current bedding and the thick sequence of essentially uniform lithology also suggest that the muscovite schist and chlorite-muscovite schist were derived from graywackes. The actinolite-chlorite schist, on the other hand, approaches a spilite in composition. The discrepancy in iron oxides is probably due in large

TABLE 3

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	59.9	58.1	64.7	58.4	50.6	51.2
Al_2O_3	21.0	20.0	14.8	15.5	17.3	13.7
FeO	0.7	—	5.8	6.5	3.5	12.0
MgO	1.1	5.4	2.2	2.5	9.0	4.6
CaO	2.9	2.1	3.1	3.1	7.9	6.9
Na_2O	5.1	4.6	3.1	1.3	4.7	4.9
K_2O	2.2	2.0	1.9	3.3	—	0.8
H_2O	1.1	2.8	2.4	5.0	3.0	1.9
Others (a)	6.7	5.0	3.4	4.4	4.0	4.0

(a) Mostly FeO, CaO, CO_2, and TiO_2 for columns 1, 2, and 5; mostly TiO_2, CO_2, P_2O_5 and MnO for columns 3, 4, and 6.

Composition of principal Pelona schist rock types compared with average graywacke, shale and spilite. Computations based on chemical compositions as given in Dana's textbook of mineralogy, W. E. Ford, 1932, 4th ed., John Wiley & Sons, Inc., 851 p. Albite is assumed to have the composition $Ab_{95}An_5$, albite-oligoclase $Ab_{85}An_{15}$, and oligoclase $Ab_{70}An_{30}$. Chlorite has been assumed to be pennine. Actinolite has been assumed to have Mg:Fe::3:2.

(1) Muscovite schist, Bouquet Canyon, California. Computed chemical composition derived from average mineral composition (fig. 4).

(2) Chlorite-muscovite schist, Bouquet Canyon, California. Computed chemical composition derived from average mineral composition (fig. 4).

(3) Average graywacke, F. J. Pettijohn, 1957, Sedimentary rocks, 2d ed., p. 307, Harper & Brothers.

(4) Average shale, F. W. Clarke, 1924, Data of geochemistry, U. S. Geol. Survey Bull. 770, p. 30.

(5) Actinolite-chlorite schist, Bouquet Canyon, California. Computed chemical composition derived from average mineral composition (fig. 4).

(6) Average spilite, N. Sundius, Geol. Mag., v. 67, p. 9, 1930.

part to the composition assumed for chlorite, actinolite, clinozoisite, and epidote in the calculations.

A general change in composition can be noted in the section of the Pelona schist that is exposed in Bouquet Canyon (table 1). The lower part of the section is dominantly actinolite-chlorite schist and chlorite-muscovite schist, whereas the upper part is mostly muscovite schist with minor amounts of quartzite and marble. The lower actinolite-chlorite schist may have been formed from basic volcanic rocks (spilites); the chlorite-muscovite schist may be reworked volcanic detritus eroded from nearby regions. The muscovite schist was probably graywacke. The beds of limestone and quartzite clearly are of sedimentary origin. The purity of the quartzite indicates that originally it was orthoquartzite or possibly chert.

This presumed set of original rocks, including graywacke, basic volcanics, and minor orthoquartzite (chert?) and limestone, is of the type commonly ascribed to eugeosynclinal deposits (Kay, 1951, p. 86). If this interpretation is correct, then the present widespread distribution may be the result of original deposition over a large area rather than dislocation by later tectonic events (for example, by major strike-slip faulting).

AGE

The Pelona schist has been correlated with the Rand schist by Hulin (1925, p. 29-31). He believes the Rand schist is Precambrian in age because its degree of metamorphism is in marked contrast to that of nearby lower Paleozoic strata. Also some fragments of what may be Rand schist are present in some rocks of possible Paleozoic age.

Miller (1946, p. 516-517) believes that the Pelona schist is late Precambrian in age, and that it is older than the plutonic rocks of the San Gabriel complex. These plutonic rocks are known to inject the metasedimentary Placerita formation of presumed early Precambrian age. These intrusive rocks, in turn, have been injected by more widespread plutonic rocks in the San Gabriel Mountains, one unit of which has been zircon age-dated as Precambrian (Neuerburg and Gottfried, 1954, p. 465). Wallace (1949, p. 787) suggests that the Placerita formation may be a correlative of the Pelona schist, a view that the writers consider reasonable. The only definite age assignment that can be made for the Pelona schist is pre-Tertiary, as the schist has been intruded by granitic rocks similar to those of the Cretaceous(?) Sierra Nevada batholith. If the Placerita formation is a higher metamorphic rank correlative of the Pelona schist, then the Pelona schist is Precambrian as well. Certainly the question merits further attention and study.

STRUCTURE

The central Sierra Pelona is a southwestward-plunging asymmetrical anticline with a smaller fold developed along the oversteepened south flank (fig. 2). Extensive landslides, creep, and a heavy brush cover obscure much of the geology, and it is possible that other folds or faults of a mappable scale may be present in the map area. The only mappable units, the quartzite and marble sequences, suggest that the structural interpretation shown is reasonably accurate, although some small isoclinal folds may also be present. A brief reconnaissance of the western end of the range indicates that the main antinclinal fold continues to plunge westward and probably continues under the overlapping Tertiary sedimentary rocks. Eastward along the southern flank of the range the structural complexity increases, as shown by several additional southwest-plunging folds as well as some probable faults extending northeastward into the range from the Soledad basin.

Foliation in the schist is prominent and is parallel to bedding in most places. Thus the main structure of the range as outlined by both bedding and foliation was determined by observing the attitudes of the contacts between contrasting lithologies and foliation within each lithologic unit. Foliation is parallel to the axial planes of minor folds wherever these were observed. The widths of the minor folds are only a few feet or tens of feet.

The minor fold axes in the intricately contorted marble and quartzite units consistently plunge 10-20 degrees south-southwest at angles that approximate, although in general they are steeper than, the plunge of the major anticlinal axis. A lineation in the schist, formed by wrinkling in the plane of foliation, also plunges southwest, although somewhat more steeply than the minor fold axes. This is illustrated by representative attitudes on the geologic map

(fig. 2). A second lineation in the schist, weakly developed and not shown on the geologic map, is a wrinkling of the foliation plane that plunges down dip.

Two subvertical joint sets occur in the quartzite that is interbedded with the marble. The angles of intersection between the two sets are 60° and 120°, with the 120° angle bisecting the axial planes of the minor folds. The fact that the folds plunge and the joints are essentially vertical suggests that the angular symmetry is coincidental and that the jointing developed later, although under similar stress conditions.

Post-metamorphic diastrophism has developed a slight shearing and granulation in the marble associated with the quartzite. In addition undulatory extinction of quartz as well as fractured clinozoisite and garnet crystals demonstrate that the schist has been affected as well. These features may have developed as the result of movements along the nearby faults (e.g., San Andreas, Pelona, Bee Canyon, etc.).

The major and minor structural features described consistently indicate a horizontal maximum compressive stress oriented along a north-northwest line and a vertical minimum compressive stress.

The probable sequence of development of these structures is as follows: metamorphism with concurrent development of foliation, minor folds and lineations; major fold development, in part later (Cenozoic deformations) although major structure the result of the main metamorphic period (probably Precambrian); jointing during waning stages of metamorphism, as well as accentuation during all later deformations; shearing and granulation, probably as result of post-metamorphic diastrophism.

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THE TEANAWAY DIKE SWARM OF CENTRAL WASHINGTON

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ABSTRACT. The Teanaway dike swarm is on the eastern flank of the Cascade Mountains and extends westward 45 miles from the city of Wenatchee. This parallel dike swarm is a minimum of five miles long (measured parallel to the dikes). The dikes intrude the already folded Paleocene (?) Swauk arkose and older rocks. Overlying the swarm is the Teanaway basalt consisting of 3,000 to 5,000 feet of lava and pyroclastics. Previous workers considered the dikes to be the feeders of the Teanaway basalt; however, initial dips show that the Teanaway was extruded from a few volcanoes, not the closely spaced dikes. Conformably above the Teanaway basalt is the Eocene Roslyn arkose.

The dike swarm is a tensional feature and the dikes locally compose up to 90 percent of the present surface although the average is much less. The dikes are nearly perpendicular to the fold axes of the Swauk arkose, suggesting that their orientation was determined by the direction of the least compression. The best developed part of the swarm is south of the Mt. Stuart massif, probably due to localization of tight folding by that buttress. The magma source may have been a body of approximately the same width as the swarm. Nearby occurrences of gabbro may be part of that body. The dikes, gabbro and Teanaway basalt appear to be genetically related.

The Teanaway dike swarm is small in comparison with other parallel dike swarms; however, it is much wider than long in contrast to other dike swarms.

INTRODUCTION

The Teanaway dike swarm was first described over 50 years ago by I. C. Russell, G. O. Smith, and F. C. Calkins in their early reconnaissance studies of the Cascade Mountains, and has received very little attention since that time.

Geologic Setting.—The oldest rocks in the area are the pre-Tertiary crystalline rocks of the Mt. Stuart or Wenatchee Mountains massif. Unconformably overlying these rocks is the Late Cretaceous or Paleocene Swauk arkose which is moderately to tightly folded along northwest to east-west trends. The Teanaway dikes intrude the previously folded Swauk and older rocks, and andesitic volcanics (not shown on the map) that locally overlie the Swauk. The Teanaway basalt, consisting of 3,000 to 5,000 feet of basaltic flows and pyroclastics, unconformably overlies the Swauk formation. Lying conformably on the Teanaway basalt is the Roslyn arkose, consisting of 3,000 to 8,000 feet of arkose, conglomerate, shale and coal beds. The Roslyn is probably middle to upper Eocene on the basis of two turtle carapaces, a fossil fish and fossil leaves (Wheeler, 1955). To the south and east all the above rocks are covered unconformably by the Mio-Pliocene Yakima or Columbia River basalt (Waters, 1955a, p. 664).

Nomenclature.—The definitions of Wentworth and Williams (1935) are used in describing the pyroclastic rocks. The mineraloids described below were identified optically. More complete descriptions and structural determinations of the basalt mineraloids have been made by Wilshire (1958).

THE DIKE SWARM

The Teanaway dike swarm occurs on the eastern flank of the Cascade Mountains in Central Washington. It extends from the city of Wenatchee westward for 45 miles, although most of the dikes are in the westernmost 25 miles, just south of Mt. Stuart where they are overlain by the Teanaway basalt

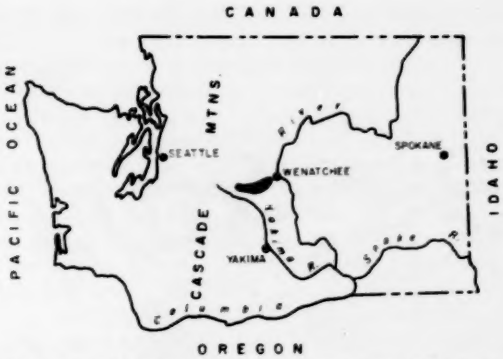

Fig. 1. Index map of Washington. The location of the Teanaway dike swarm is shown in black.

formation (fig. 1). This paper is concerned mostly with the western portion of the swarm. Because the geology of the Central Cascade Mountains is described in detail elsewhere (Foster, in preparation), only the important relations are summarized here.

Parts of the dike swarm have been described by Russell (1893, 1899), Smith (1903, 1904), Lupher (1944) and Chappell (1936). The map, figure 2, has been compiled from Smith (1904), Smith and Calkins (1906), and mapping by the writer. The following descriptions emphasize that, on the scale of the map, the dikes are shown only diagrammatically.

The individual dikes of the swarm were aptly described by Russell (1899, p. 121). They range in width from a few inches to over 160 feet with many between 15 and 60 feet wide. Their length is probably of the order of several miles but the thick vegetation of the Cascade Mountains makes tracing the dikes across valleys very difficult. Their trend commonly varies only a few degrees from N 15° E. Most of the dikes dip between 80° west and vertical.

The number of dikes in the swarm is incredible. Russell (1899, p. 121), observed,

> Practically they (the dikes) are countless. In one section near the head of Stafford Creek, about five miles southeast of Mount Stuart, fifty dikes, ranging in thickness from 15 to 60 feet, were observed in an area 3,500 feet broad, measured at right angles to their trend.

Lupher (1944, p. 29) estimated the ratio of intrusive to sedimentary rock to average one to four, and

> From the east side of Miller Peak west to the west side of Iron Peak, a distance of more than eight miles, the intrusions are so numerous as to reduce the Swauk to a series of thin sandstone slabs lying between large complex dike masses. The ridge between Standup and Bean Creeks is probably more than 90 percent basic dike material and the Swauk sandstones are preserved as occasional thin layers or lenses a few feet or a few tens of feet thick.

By comparison, at Mull and Arran in Scotland the dikes make up 3.7 percent and 7 percent of the area respectively (Barth, 1952, p. 229). In spite of the few exposures, the present author was able to map the structure of the Swauk arkose by studying the tiny septa of Swauk between the dikes. Except for slight

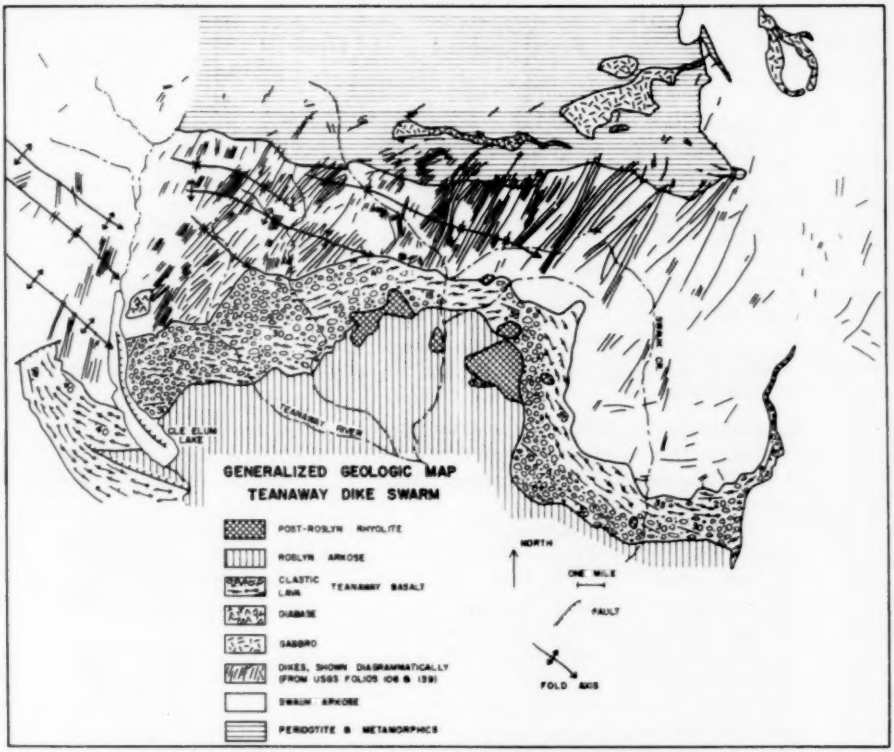

Fig. 2. Generalized geologic map of the Teanaway dike swarm.

contact metamorphism the Swauk was unaffected by the dikes. The lack of deformation of the arkose and the dikes, as well as the close spacing of the dikes, suggest that the swarm is tensional.

The swarm may extend southward beneath the Teanaway basalt formation but this appears unlikely. In the Swauk Creek drainage, erosion has removed the cover of folded Teanaway basalt and, as shown on the map, the number of dikes diminishes markedly to the south. South of Teanaway River, just off the map, the Teanaway basalt crops out and only a few dikes and intrusive bodies occur nearby (Smith, 1906; Stout, 1957).

Petrography of the Dikes.—In hand specimen, the dike rocks are dark gray and aphanitic. They have an intersertal texture and are composed on the average of 50 percent plagioclase, 30 percent pyroxene, 15 percent glass, mineraloids and chloritic material and 5 percent opaques, presumably magnetite and ilmenite. The plagioclase is in the form of elongate laths that grade from cores as calcic as An50 to rims as sodic as An33. The pyroxene grains are

anhedral to subhedral. Both pigeonite (2V near zero degrees) and augite (2V about 40 degrees) are present. The opaques occur as small disseminated grains, larger, partly resorbed grains, and elongate ragged rods.

The mineraloids or minerals in the groundmass appear to be due to alteration, perhaps deuteric, of the glassy material. Some of this material is green, pleochroic, and weakly birefringent, and occurs in felted masses commonly intermixed with opaque grains; it is believed to be chlorite. Also present is a yellow or yellow-brown material believed to be chlorophaeite. A third alteration product of the glass and the pyroxene was tentatively identified as iddingsite.

The dikes all have chilled borders in which the basalt is finer-grained and more altered and at some localities contains inclusions of the Swauk sediments.

Apparently associated with the dike swarm are a few irregularly-shaped diabase intrusive bodies. Only one is large enough to show on the map. The diabase is quite similar to the dike rock just described; it is holocrystalline rock, has an intergranular texture, and is composed of approximately 60 percent plagioclase, 25 percent augite, 10 percent pigeonite, 4 percent opaques and 1 percent chlorite. The plagioclase laths are gradationally zoned with labradorite cores (An58) and andesine rims (An30). The augite is anhedral with a few included apatite crystals. The pigeonite is light green with 2V less than 15 degrees and is in the form of small rounded grains. The magnetite occurs as large partly resorbed grains and the chlorite is interstitial. Amygdaloidal calcite is present in a few places.

Perhaps associated with the dikes (see below) are several intrusive bodies of gabbro. These bodies have not been studied by the author and the following description is from Smith (1904, p. 6). The gabbro occurs as very irregular bodies intrusive into the rocks of the Mt. Stuart massif and the Swauk formation. "Small dike-like masses indicate that probably at greater depth the gabbro mass may extend as far west as North Fork of Teanaway River." At the easternmost occurrence, the gabbro forms a lopolith in the Swauk arkose that is at least 500 feet thick.

> No diabase dikes were observed cutting the gabbro, although these dikes are shown on the areal geology map in the immediate vicinity of the gabbro areas, while many dikes of fine-grained gabbro can be traced from the main mass for short distances into the serpentine. It is possible that the gabbro represents slightly later intrusions of the same magma from which the Teanaway basalt has been erupted.

The gabbro is medium to coarse grained, holocrystalline, and is both ophitic and granular in texture. It contains plagioclase zoned with cores of basic labradorite and rims as sodic as oligoclase. The pyroxene is augite in the ophitic rocks and diallage in the granular rocks. Olivine and hypersthene are represented by alteration products. Brown hornblende is intergrown with orthoclase and pyroxene. Magnetite, ilmenite and apatite are primary minerals. Some of these rocks are altered and contain hornblende, chlorite, serpentine, leucoxene, quartz, epidote, actinolite, zoisite and kaolin.

THE TEANAWAY BASALT

The Teanaway basalt was first described by Russell in 1899 and was named by G. O. Smith in 1903. It crops out south of the dike swarm in an arcuate band up to four miles wide and unconformably overlies the Swauk and locally an andesite unit. The Teanaway basalt is concordantly followed by

the Roslyn arkose and they have been deformed together into a shallow basin.

The Teanaway basalt is composed of 3,000 to 5,000 feet of lava, pyroclastics and some sedimentary rocks. The general distribution of lithologies is shown on the map although the rugged terrain and vegetation hamper mapping the details of this complex interbedding except in favorable areas. Many of the attitudes show a marked discordance with the outcrop pattern, and this is interpreted to mean that the rocks were initially deposited on the slopes of volcanoes. This description shows that a stratigraphic section would be of very limited value.

In spite of the evidence clearly indicating volcanoes, Smith (1904, p. 6) observed,

> In exceptionally favorable exposures the vertical dike can be traced, as it cuts the sandstone, to a point where the narrow dike abruptly widens out and becomes a part of the horizontal or gently inclined flow. The evidence is conclusive that the Teanaway basalt was erupted through many fissures rather than from a large volcanic center.

It is interesting that Turner and Verhoogen (1951, p. 176), in discussing dike swarms all over the world, note the "absence of authentic instances of transition between individual flows and individual dikes remains an unexplained anomaly."

Petrography

Basalts.—Most of the basalts are fresh unaltered rocks. Most are aphanitic and some have the silky sheen associated with glassy rocks. All are dark gray in color. A few have amygdules filled with quartz, chalcedony, calcite, chlorite or chlorophaeite.

In thin section, most of these rocks have an intersertal texture. A typical basalt is composed of about 20 percent plagioclase, 15 percent augite (2V of 35 to 40 degrees), 5 percent opaques, probably magnetite and ilmenite, 45 percent glassy material and 15 percent amygdules. The subhedral plagioclase laths are gradationally zoned from cores of labradorite (An52) to rims of oligoclase (An26). The shapeless grains of pyroxene contain opaque inclusions; many of the opaque grains are irregular rods in the glassy material and in addition, the glass is charged with opaque dust. The amygdules are irregularly shaped and are commonly surrounded by glassy material.

All gradations exist between the rocks described and more glassy rocks that contain only a few microlites of plagioclase in opaque glass. At a few localities, pillow structures with glassy selvages on the ellipsoidal basalt were noted.

Clastics.—The most common pyroclastic rock in the Teanaway is a green lapilli-tuff. In hand specimen, this rock is dull green in color and composed of very angular, poorly-sorted lithic fragments up to three quarters of an inch in diameter set in a green groundmass. The lithic fragments are usually different shades of green, but purple, red and brown fragments are not uncommon. This rock weathers to a brown or a red-brown color and is commonly well bedded.

Under the microscope, the overall aspect of these rocks is alteration. The fragments seem to be composed predominantly of green chlorite, much opaque material and some finely divided quartz. Much of the groundmass has the same

composition, but in many specimens, the groundmass is extremely fine grained, green-gray in color, and is a dark gray between crossed nicols. This material, and probably part of what is called chlorite both in the groundmass and in the fragments, may be nontronite (c.f. Allen and Scheid, 1956, p. 294-312). A few of the fragments contain microlites of altered sodic andesine.

Amygdules of calcite, quartz and chlorite are ubiquitous. Associated with the amygdules are branching calcite veinlets in both the groundmass and some of the fragments.

The finer-grained pyroclastic rocks are more altered than the lapilli-tuffs, but are otherwise similar.

Sedimentary rocks were found scattered throughout the Teanaway basalt although they are of limited extent. Typical of these rocks is a sharpstone conglomerate composed of angular and sub-rounded fragments up to three inches in diameter of quartz, argillite, and basalt, in a sand-size groundmass of poorly sorted fragments of the same material.

MODE OF EMPLACEMENT

Dike swarms are tensional features. In the case of a radial dike swarm around a volcano, such as that described at Sunlight Basin by Parsons (1939), it is not difficult to visualize a magma welling up beneath the volcano and applying the tensional forces. The dike swarms that are elongate parallel to the dikes may have formed as a result of lateral movement of the magma in a tension zone created by a flexure. A probable occurrence of such a swarm in Greenland was described by Wager and Deer (1938).

Dike swarms have been discussed by Anderson (1951) who believes (p. 24) that most dikes are emplaced by the hydrostatic force of the magma and are aligned perpendicular to the least compression. He implies that regional forces control dike swarms. The Teanaway swarm appears to be controlled by the same forces that folded the Swauk sediments. As shown on the map, the dikes are all perpendicular or nearly perpendicular to the fold axes. Thus they are aligned perpendicular to the least compression.

The control of the dikes by the Swauk folding is also shown by the fact that the most extensive development of the swarm is where the Swauk arkose is most strongly folded. This is the westernmost 25 miles of the swarm, just south of the Mt. Stuart massif. The basal Swauk lithologies show that the Mt. Stuart massif was high during the Swauk deposition and the wrapping of the Swauk fold axes around the massif indicates that it was positive during Swauk folding (Foster, in preparation). The positive nature of this block localized the Swauk folding and the Swauk is vertical to overturned near the massif but becomes less steeply folded to the south. The diminution of dikes to the south is noted above. The fold axes were not mapped by the writer in the Swauk Creek drainage; however, their trend is generally northwest-southeast. The almost perfect parallel alignment of the dikes suggests that they are controlled in detail by jointing in the competent Swauk arkose. The Swauk arkose unconformably overlies a serpentinized peridotite that forms the southern part of the Mt. Stuart massif. This contact is vertical or almost vertical and is commonly sheared. At a few places the dikes extend into the peridotite and change

to very irregular bodies. Some of the changes are due, at least in part, to faulting at the contact.

The source of the magma that fed the dikes is a separate problem. The dike magma may have moved some distance horizontally and Anderson (1951) believes that many dikes are emplaced by horizontally moving magma. In a swarm elongate perpendicular to the dikes, such as the Teanaway swarm, it appears likely that the immediate magma source must have been elongate also. If the periodotite underlies the folded Swauk at depth as it does at the surface, a likely horizon for the body would be either in the peridotite or on the contact between the peridotite and the Swauk. Possible credence is given this hypothesis by the gabbro bodies in the Swauk arkose and the peridotite in the area north of the dike swarm.

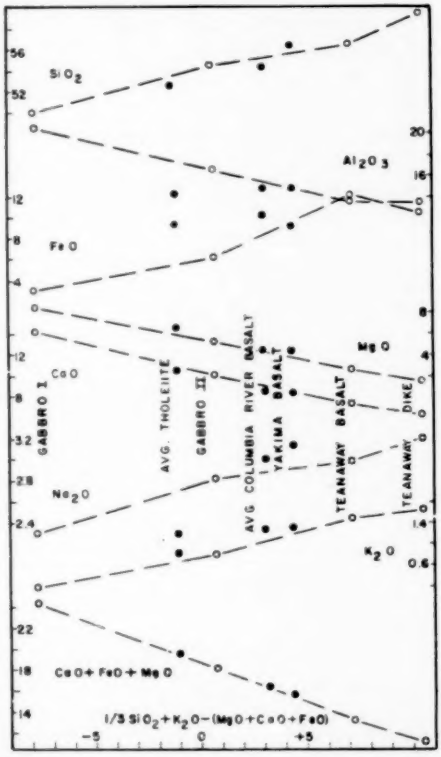

Fig. 3. Variation diagram comparing the Teanaway rocks with the Columbia River basalt (Yakima basalt) and average tholeiite. The Teanaway rocks are indicated by open circles.

PETROLOGY

The chemical nature of the Teanaway rocks is interesting. Table 1 summarizes and compares the Teanaway rocks with the Columbia River basalt and the world average of tholeiitic basalt. The Teanaway rocks, with the possible exception of the dike rock which may be contaminated by wall rock inclusions, are chemically similar to the Columbia River basalt which is a flood basalt and considered by most petrologists to be a tholeiitic basalt. Therefore the Teanaway basalt is considered to be a tholeiite. However, the Columbia River basalt is chemically different from the average tholeiitic basalt. Waters (1955b, p. 705, 708) notes that the Eocene basalts of the Cascades are close to Nockolds' tholeiitic basalt and that the Columbia River basalt is close to Nockolds' tholeiitic andesite.

The chemical composition of gabbro I (Smith 1904, p. 6) is quite similar to the high alumina magma of Yoder and Tilley (1957, p. 156). This rock, however, is altered and may not be representative of the gabbro.

The variation diagram, figure 3, shows the relationship between a Teanaway basalt flow, a dike and the gabbro which, as discussed earlier, may be the source of the dike swarm. These curves suggest a genetic relationship, but certainly do not prove it. An analysis of the Columbia River basalt is also plotted on the diagram and, although chemically quite similar, falls far enough off the curves to be distinguishable from the Teanaway rocks.

The Teanaway dike swarm is composed of tholeiitic basalt and was an early feature in the volcanic history (unlike Mull and Skye). The associated basalts contain much pyroclastic material in sharp contrast to chemically similar basalts such as the Columbia River basalt.

TABLE 1
Chemical Analyses

	1	2	3	4	5	6	7
SiO_2	53.35	57.21	48.58	51.98	54.50	52.31	50.83
Al_2O_3	12.90	12.99	20.23	15.99	14.43	14.38	14.07
Fe_2O_3	2.64	3.28	1.26	3.10	2.17	2.47	2.88
FeO	11.28	10.18	3.02	5.88	8.80	9.95	9.00
MgO	2.68	1.59	7.59	5.09	4.25	4.46	6.34
CaO	6.96	5.97	14.01	9.68	8.01	8.37	10.42
Na_2O	2.83	3.07	2.25	2.71	3.05	2.94	2.23
K_2O	1.40	1.61	.19	.81	1.29	1.26	.82
H_2O^+	1.76	1.03	.28	.48	1.09	0.74	.91
H_2O^-	.91	.68	2.68	2.08	.29	0.39	—
P_2O_5	.45	.44	tr	.31	.21	0.36	.23
TiO_2	2.44	1.72	.09	1.71	1.69	2.10	2.03
MnO	.25	—	tr	.10	.10	0.21	0.18

1. Teanaway basalt, Smith 1904 p. 6, Analyst: W. F. Hillebrand
2. Teanaway dike, Smith 1904 p. 6, Analyst: W. F. Hillebrand
3. Gabbro I, Smith 1904 p. 6, Analyst: H. N. Stokes
4. Gabbro II, Smith 1904 p. 6, Analyst: H. N. Stokes
5. Yakima basalt (Columbia River basalt), Smith 1904 p. 8, Analyst: G. Steiger
6. Average of 6 Columbia River basalts, Waters 1955 b, p. 705
7. Average tholeiitic basalt, Nockolds, 1954

SUMMARY

The Teanaway dike swarm intruded the already folded Swauk formation along tensional fractures with very little disturbance of the Swauk sediments. In some areas the dikes form up to 90 percent of the surface area. The Teanaway basalt formation, consisting of 3,000 to 5,000 feet of basalt flows and pyroclastics, is later than the dike swarm and is not cut by the dikes. The attitudes of the strata in the Teanaway basalt are discordant with the map pattern of the formation, suggesting that the rocks were deposited on the flanks of volcanoes with moderate initial dips. The nearness in time, place and composition of the dike swarm to the Teanaway basalt suggested a genetic relation ship to earlier workers; however, the presence of volcanoes in the overlying Teanaway basalt shows that only a few of the thousands of dikes could have been feeders.

The Teanaway swarm is small in comparison with other parallel dike swarms; however, it is much wider than long in contrast to other dike swarms.

The dikes are perpendicular to the fold axes in the intruded Swauk sediments suggesting that the emplacement was controlled by regional forces. The dikes are more numerous in the more strongly folded areas. Because the swarm is elongate perpendicular to the dikes, the magma source must have been as wide as the swarm unless the magma moved large distances horizontally. Several nearby bodies of gabbro of the same general age are possibly part of the source body.

Comparison of the chemical and mineralogical nature of the dikes, Teanaway basalt, and gabbro are also suggestive of a genetic relationship.

The Teanaway rocks should probably be classed as tholeiitic basalt; however, the nature of the Teanaway basalt is much different from the nearby tholeiitic Columbia River basalt.

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EQUILIBRIA OF RED HgS (CINNABAR) AND BLACK HgS (METACINNABAR) AND THEIR SATURATED SOLUTIONS IN THE SYSTEMS $HgS–Na_2S–H_2O$ AND $HgS–Na_2S–Na_2O–H_2O$ FROM 25°C TO 75°C AT 1 ATMOSPHERE PRESSURE*

F. W. DICKSON and GEORGE TUNELL

ABSTRACT. The solubilities of red HgS (cinnabar) and black HgS (metacinnabar) in aqueous Na_2S solutions (system $HgS–Na_2S–H_2O$) have been determined at 25°C, 50°C, and 75°C at one atmosphere pressure. The solubility of red HgS (cinnabar) in aqueous Na_2S–NaOH solutions (system $HgS–Na_2S–Na_2O–H_2O$) has been determined at 25°C and 75°C at 1 atm. pressure.

Chief conclusions resulting from the study are: the solubility of HgS is appreciable in Na_2S and Na_2S–NaOH solutions at all three temperatures; the solubility of HgS in Na_2S solutions is markedly greater in the presence of NaOH; the solubilities of both red and black HgS decrease with increasing temperature, the solubility of black HgS diminishing at a greater rate than the solubility of red HgS; dilution of a saturated solution of HgS in either Na_2S or Na_2S–NaOH causes precipitation of HgS; and any process that diminishes the Na_2S concentration (such as acidification, oxidation) causes HgS to precipitate.

INTRODUCTION

The ore minerals of many ore deposits are metal sulfides that are thought to have been deposited from solutions containing sulfur and water, along with other constituents such as carbon dioxide, the halogens, and boron. The need for systematic studies of equilibria in systems containing metal sulfides, water, and other constituents was pointed out by Tunell in his address as retiring president of the Mineralogical Society of America (1951, p. 174-175). From equilibrium diagrams of such systems the change of solubility of metal sulfides caused by variations in temperature, pressure, or by chemical reactions, could be deduced, and mineral sequences predicted. Graton, in the chapter entitled "Ore Deposits" in the Fiftieth Anniversary Volume of the Geological Society of America, stated that "The emphasis of Wells and of Lindgren on solubility as the key to sequence seems sound; yet the solubility about which we need to know is not that in the usual laboratory sense, but that actually existing in the ore solutions and probably changing as the episode of deposition goes on. About such solubility our knowledge remains all too meager. That is to say, we could establish mineral sequence if we knew the changing solubility characteristics in the ore solutions" (1941, p. 485 and p. 503). If in nature mineral associations are found that agree with predicted sequences, we would have direct evidence that ore solutions were similar to some of the solutions studied in the laboratory.

That the genesis of cinnabar in mercury ore deposits is particularly suitable for physico-chemical investigation was pointed out by Gallagher (1946, p. A6). He stated that "the advantages offered by cinnabar deposits as a subject for laboratory investigation into the basic principles of ore deposition (which is an important, but almost untouched, field of investigation) are (1) simplicity of mineralogy and hence of variables, (2) low temperatures and pres-

* Institute of Geophysics Paper Number 100, University of California, Los Angeles, California.

sure, (3) presence of advantageous textural peculiarities, (4) apparently greater uniformity of origin than most ore deposits, (5) an abundance of geologic field data, and (6) a goodly number of men who have [field] experience in the subject." It appeared to the authors that Knox's (1906) study of the solubility of HgS in aqueous Na_2S solutions and aqueous Na_2S–NaOH solutions could serve as the starting point for an investigation of the solubility of HgS in alkaline sulfide solutions at 25°C and higher temperatures. For such reasons it seemed that a study of mercury ore deposits and chemical aspects of their origin would be feasible and fruitful.

This paper presents the results of the laboratory portion of a combined field and laboratory investigation of the geochemistry and petrography of mercury ore deposits. The solubility of HgS in alkaline sodium sulfide solutions was measured at several temperatures at atmospheric pressure to determine the influence of changing physical and chemical conditions on the solubility of HgS. The saturation curves of red HgS (cinnabar) and black HgS (metacinnabar) in the system HgS–Na_2S–H_2O was determined at 25°C, 50°C, and 75°C. The saturation surfaces of red HgS (cinnabar) in the system HgS–Na_2S–Na_2O–H_2O were determined at 25°C and 75°C.

PREVIOUS WORK

The ease with which mercury compounds can be volatilized led some ore geologists of the nineteenth century to postulate that mercury was transported in the vapor phase, perhaps as metallic mercury or mercuric chloride. Christy (1879) pointed out, however, that the principal ore mineral of mercury deposits was cinnabar (red HgS), and that determination of the type of solution in which mercury sulfide can be transported and from which cinnabar can be deposited would solve the problem of the origin of nearly all mercury ore deposits. He rejected vapor transport of HgS because of the excessively high temperature he felt would be required to volatilize appreciable quantities of HgS. The association of cinnabar with the silica and carbonate minerals was cited as evidence that mercury sulfide must have been carried in aqueous solution, and Christy turned his attention to types of aqueous solutions that might possibly transport HgS.

In Christy's time chemical data on the solubility of HgS were scanty. It was generally known, however, that HgS is quite insoluble at room conditions in most solutions except those containing sulfide ion; even in sulfide solutions HgS had been demonstrated to be essentially insoluble in the presence of CO_2, H_2S, or elemental sulfur. No work had been done on the solubility of HgS in solutions containing these substances at elevated temperatures and pressures, which led Christy to carry out experiments during which he exposed metastable black HgS (metacinnabar) to the action of various solutions for several hours at temperatures of 200°C to 250°C and at pressures of about 17 to 34 bars. He reasoned that if the black HgS inverted to the stable red HgS in contact with a particular solution, the HgS must have had an appreciable solubility in order to allow the exchange of material required for recrystallization. Solutions of the following substances were found to be effective in promoting recrystallization: K_2S, KHS, and H_2S. $NaHCO_3$ and Na_2SiO_3 were ineffective

unless charged with H_2S. Christy concluded that "these [mercury] deposits as they exist in situ are the immediate result of the action of solutions of alkaline carbonates containing also alkaline sulphides" (1879, p. 463).

Becker (1888), in addition to compiling extensive field data on mercury ore deposits presented the results of laboratory experiments designed to illuminate the probable nature of the mercury ore solutions. These laboratory studies led to the following conclusions: HgS is appreciably soluble in alkaline sulfide solutions; the amount of HgS that dissolves is an increasing function of the sodium sulfide concentration; HgS is very slightly soluble in NaHS; and dilution of saturated solutions of HgS in Na_2S causes precipitation of black HgS. He supposed that in nature precipitation of HgS took place on diminution of pressure and temperature, by reaction with acids, or by dilution of saturated solutions.

Knox (1906) made the first quantitative studies of the solubility of HgS in Na_2S and Na_2S–NaOH solutions (tables 1, 2, and 3). He pointed out that the amount of HgS that dissolves is a function of the sulfide ion concentration according to the following equations:

$$m\ HgS + n\ S^{=} \rightarrow (HgS)_m S_n^{=}.$$

$$K = \frac{[(HgS)_m S_n^{=}]}{[HgS]^m\ [S^{=}]^n}\ .$$

Where formulas in brackets indicate activities, and K denotes the equilibrium constant.

Sodium sulfide is extensively hydrolysed in aqueous solution:

$$S^{=} + H_2O \rightarrow HS^{-} + OH^{-}\ ,\quad K_1 = \frac{[HS^{-}]\ [OH^{-}]}{[S^{=}]} = \frac{K_w}{K_{HS^{-}}}\ ,$$

$$HS^{-} + H_2O \rightarrow H_2S + OH^{-}\ ,\quad K_2 = \frac{[H_2S]\ [OH^{-}]}{[HS^{-}]} = \frac{K_w}{K_{H_2S}}\ ,$$

Where

$$K_w = [OH^{-}]\ [H^{+}]\ ,\ K_{HS^{-}} = \frac{[H^{+}]\ [S^{=}]}{[HS^{-}]}\ ,\quad K_{H_2S} = \frac{[H^{+}]\ [HS^{-}]}{[H_2S]}\ .$$

The degree of hydrolysis of Na_2S is greater in dilute solutions, which in effect diminishes the amount of $S^{=}$ ion available to react with HgS. Inspection of table 1 shows that the ratio of dissolved HgS to total Na_2S regularly diminishes with decreasing Na_2S concentration. The ratio of dissolved HgS to Na_2S concentration (expressed in moles per liter), at constant Na_2S, increases if NaOH is added to suppress the hydrolysis (see table 2), and approaches unity at the extreme NaOH concentrations. Knox concluded that HgS reacts with $S^{=}$ to form a complex anion with the formula $HgS_2^{=}$. By e.m.f. measurements he obtained added evidence that this formula is correct.

Black HgS is appreciably more soluble than red HgS at 25°C at all concentrations of Na_2S. The ratio of dissolved black HgS to dissolved red HgS for

equal concentrations of Na_2S apparently decreases with increasing Na_2S concentration (table 1).

The solubility of red HgS decreases with increased temperature (table 3). Knox considered three factors to be involved in the change of solubility: (1) a probable increase in the solubility of HgS in water caused by a rise in temperature; (2) lowered solubility caused by increased hydrolysis of Na_2S at the higher temperature; and (3) lowered solubility caused by decreased stability of the complex ion at the higher temperature. The last two effects more than overcome the influence of the first.

Knox's work was well done, and it has proved useful, particularly to ore geologists speculating on the origin of mercury ore deposits. However, it was not a complete determination of equilibrium relations since he did not determine the final concentrations of Na_2S and NaOH in the equilibrium mixtures. His procedure involved allowing HgS to react with solutions of Na_2S and NaOH of known initial concentration until the solutions were saturated with HgS. He then determined the equilibrium concentration of HgS only. His tables present initial concentrations of Na_2S and NaOH together with corresponding final concentrations of HgS.

TABLE 1

Solubilities of Red and Black HgS in Na_2S Solutions at 25°C According to Knox

Concentration of Na_2S Moles/liter	Red HgS Dissolved Moles/liter	Ratio of Red Hgs to Na_2S	Black HgS Dissolved Moles/liter	Ratio of Black HgS to Red HgS
2.030	1.144	0.5635	—	—
1.52	0.7832	0.5153	0.8561	1.09
1.015	0.4423	0.4328	0.5002	1.13
0.755	0.2878	0.3812	0.3336	1.16
0.50	0.1500	0.3006	0.1805	1.20
0.25	0.04544	0.1818	0.05622	1.24
0.10	0.008241	0.0824	0.01085	1.32

Allen, Crenshaw, and Merwin (1912) studied the equilibrium relations of red and black HgS in an effort to establish the physical chemical conditions attending the origin of cinnabar and metacinnabar in nature. They reported that black HgS, metacinnabar, is obtained only from acidic solutions, whereas red HgS, cinnabar, is obtained usually from alkaline solutions, although red HgS can form in acid solutions under certain conditions. Because cinnabar is far more abundant than metacinnabar in nature, their observation that cinnabar forms more easily in alkaline solutions and metacinnabar only in acid solutions was offered as evidence that most HgS in nature has been deposited from alkaline solutions. It should be pointed out, however, that Becker had demonstrated earlier that metacinnabar can be precipitated from alkaline solutions by merely diluting saturated solutions of HgS in Na_2S.

TABLE 2

Solubility of Red HgS in Na_2S at various NaOH Concentrations at 25°C According to Knox

Concentration of Na_2S Moles/liter	Red HgS dissolved (moles per liter) in Na_2S solution	in Na_2S + 0.5 n NaOH	in Na_2S + 1.0 n NaOH
1.015	0.4423	—	0.673
0.755	0.2878	—	0.485
0.50	0.1500	0.2483	0.302
0.25	0.04544	0.1106	0.148
0.10	0.008241	0.03962	0.0563

Concentration of Na_2S Moles/liter	Red HgS dissolved (moles per liter) in 4.48 n NaOH	in 4.67 n NaOH	in 7.7 n NaOH	Ratio of HgS to Na_2S in 7.7 n NaOH Moles HgS/Moles Na_2S
1.015	—	—	0.9167	0.903
0.755	—	—	—	—
0.50	0.435	—	0.4637	0.927
0.25	—	0.225	0.2369	0.948
0.10	—	0.0903	0.09634	0.963

TABLE 3

Solubilities of Red HgS at 33°C and 25°C and Temperature Coefficients of Solubility According to Knox

Concentration of Na_2S Moles/liter	Red HgS dissolved 33°C Moles/liter	25°C Moles/liter	Concentration Difference Moles/liter	Percentage Change per °C
0.755	0.2828	0.2878	−0.0050	−0.22
0.5	0.1465	0.1500	−0.0035	−0.29
0.25	0.04360	0.04544	−0.00184	−0.51
0.10	0.007887	0.00824	−0.00035	−0.53

Dreyer (1940) first called attention to Knox's work, previously unnoticed by geologists, in a paper which summarized previous chemical and geological studies pertinent to the problem of the origin of mercury ore deposits together with the results of his own chemical and petrographic investigations. He concluded from his studies that HgS is transported in nature in Na_2S solutions. He thought that HgS precipitates from such solutions by increased acidity, by dilution, by reaction with wall rock, or by evaporation. Thompson (1954, p. 188-189) correctly objected to Dreyer's proposed evaporation mechanism, pointing out that Knox's work demonstrated that HgS becomes more soluble at higher Na_2S concentrations.

Saukov (1946) presented a review of the geochemistry of quicksilver deposits together with experimental determinations of the solubility of black HgS in Na_2S solutions at 17°C and at 57°C (tables 4 and 5). Saukov emphasized the importance of dilution and decrease of alkalinity in precipitating HgS from Na_2S solutions.

Saukov's determination of the solubility of black HgS in Na_2S solutions at 17°C yielded lower values than those reported by Knox (table 1) at 25°C and those obtained by us at 25°C (table 12). The lower solubility reported by Saukov at the lower temperature is anomalous; the solubility of HgS should be greater at the lower temperature. Moreover, Saukov's own data are not consistent. Comparison of his 17°C data in table 4 with his 17°C data in table 5 shows that the two sets of data do not agree.

Krauskopf (1951, p. 498-523), by chemical thermodynamic methods, evaluated possible mechanisms for transporting mercury in nature. Three processes were shown to be thermodynamically feasible: (1) vapor transport of metallic mercury; (2) vapor transport of mercuric chloride; and (3) transport in slightly alkaline sulfide solutions as the $HgS_2^=$ complex.

The amounts of HgS that Na_2S solutions of various pH values are capable of dissolving at 25°C were calculated by Krauskopf (table 6). For example, a solution of pH 7 that contains 0.1 mole per liter total sulfur is capable of dissolving 7.5×10^{-9} moles HgS per liter, or 1.5×10^{-6} grams HgS per liter; if the solution contains 0.001 moles per liter total sulfur, it must have a pH of approximately 8.5 to hold the same amount of HgS. Krauskopf estimated 10^{-7} grams per liter to be a reasonable minimum concentration necessary in an ore-forming solution. It thus appears that slightly alkaline sodium sulfide solutions can transport geologically significant amounts of mercury at 25°C. HgS is less soluble in Na_2S solutions at higher temperatures but by extrapolating solubility data Krauskopf estimated that at 300°C the solubilities do not decrease to values as small as 1/100 of those presented in table 6.

TABLE 4

Solubility of Black HgS in Na_2S Solutions at 17°C According to Saukov

Concentration of Na_2S Moles/liter	Concentration of HgS Moles/liter
0.5	0.131
0.25	0.0449
0.125	0.00801
0.05	0.00216
0.025	0.00058
0.005	0.000048

TABLE 5

Solubility of Black HgS in Na_2S Solutions at 17°C and at 57°C According to Saukov, and Temperature Coefficients of Solubility

Concentration of Na_2S Moles/liter	Concentration of HgS Moles/liter		Concentration Difference Moles/liter	Percentage Change per °C
	17°C	57°C		
0.5	0.1136	0.08088	−0.0327	−0.72
0.05	0.001922	0.001444	−0.000478	−0.62

TABLE 6

Solubility of HgS in Na_2S Solutions at Various pH Values at 25°C. as Calculated by Krauskopf

pH	Dissolved HgS if total dissolved S is 0.1 mole/liter		Dissolved HgS if total dissolved S is 0.001 mole/liter	
	Knox-Kubli-Saukov (mole/liter)	Knox (mole/liter)	Knox-Kubli-Saukov (mole/liter)	Knox (mole/liter)
1	1.5×10^{-20}	1.4×10^{-20}	1.5×10^{-22}	1.4×10^{-22}
4	1.5×10^{-17}	1.4×10^{-17}	1.5×10^{-18}	1.4×10^{-18}
7	7.5×10^{-15}	7.0×10^{-15}	7.5×10^{-17}	7.0×10^{-17}
10	1.5×10^{-5}	1.4×10^{-5}	1.5×10^{-7}	1.4×10^{-7}
13	0.007	0.012	7.0×10^{-5}	1.2×10^{-4}

Preliminary results of our investigation of the solubility of red HgS and black HgS in solutions of the system HgS–Na_2S–H_2O at 25°C were published in 1955 (Dickson and Tunell). The values reported have been modified slightly by experimental work carried out by us since that time and the revised data are presented in this paper.

EXPERIMENTAL PROCEDURES

Baker and Adamson reagent grade red HgS was used. Black HgS was synthesized by precipitation from HgS–Na_2S solutions. "Baker Analysed" reagent grade $Na_2S \cdot 9H_2O$ was rinsed with distilled water to remove impurities adhering to the surface of the crystals. "Baker Analysed" reagent grade NaOH was used to make up carbonate-free saturated NaOH stock solutions.

Bottles fabricated from "Teflon" (tetrafluorethane) proved impermeable and resistant to chemical attack at temperatures up to 75°C, and hence were used for all experiments. Polyethylene bottles were satisfactory for short-time runs at 25°C but at higher temperatures they became soft and permeable. Glass bottles are attacked by Na_2S solutions and were not used. Constant temperatures were maintained by the use of two constant temperature baths; a 25 gallon water bath was used at 25°C and a 10 gallon oil bath was used at 50°C and at 75°C. Heat was supplied by knife type heaters controlled by mercury thermoregulators and electronic relays. Temperatures were set according to Beckman thermometers previously calibrated with a reference platinum resistance thermometer. The temperature of the 25°C bath was held constant within ± 0.02°C, and the temperatures of the 50°C and the 75°C baths were each held constant within ± 0.05°C. The baths were stirred vigorously with three-bladed screw type mixers.

Each experimental mixture was made up freshly when needed to avoid reaction with oxygen in the air. Rinsed $Na_2S \cdot 9H_2O$, HgS, boiled distilled H_2O, and in the quaternary system studies, concentrated NaOH solution, were weighed into teflon containers. The teflon cap was tightly screwed into place and "Duco" cement was placed at the junction of the cap and the top of the bottle as an added precaution to prevent leakage. Experimental mixtures containing red HgS were agitated for at least two days. Comparison of the HgS content of solutions agitated two weeks with the HgS content of solutions agi-

tated two days showed no significant difference, indicating that equilibrium was attained in two days.

Such long runs usually were not possible with black HgS. The inversion of black HgS to the more stable red HgS is accelerated in the presence of Na_2S solutions. That equilibrium between the black HgS and the solution had been attained during the times used, however, was strongly implied by the agreement in HgS concentration of different samples allowed to react for different lengths of time, and by the falling of experimental points on smooth curves. Solutions containing concentrated Na_2S were allowed to react with black HgS for four hours; more dilute solutions could be allowed to react for as long as two days.

Indirect evidence that equilibrium had been approached was the recrystallization of black HgS which took place during a few hours contact with Na_2S solution. The black HgS used as starting material was not well crystallized because it had been precipitated rapidly from HgS–Na_2S solutions. When examined by the x-ray spectrometer immediately after precipitation, the original black HgS showed only crude broad peaks at the position of the major metacinnabar peaks. X-ray examination of black HgS after six hours contact with Na_2S solution showed that the crystallinity had increased to such a degree that it was apparently equal to the crystallinity shown by natural metacinnabar. For crystallization to take place exchange of HgS from the solid phase to the solution, back to the solid phase is required.

The solid phases were identified by use of the petrographic microscope and the x-ray spectrometer. The microscope proved much more sensitive than the x-ray spectrometer for detecting small amounts of red HgS in black HgS.

Analytical Procedure

Saturated solutions were analyzed by a procedure developed when other analytical procedures were found to be unsatisfactory for solutions of the types encountered in this study. The method involves using H_2O_2 to oxidize $S^=$ ion to $SO_4^=$ ion according to the following reaction:

$$4H_2O_2 + HgS_2^= \rightarrow SO_4^= + HgS \quad .$$

All Na_2S is thereby converted to Na_2SO_4, which can be determined by standard procedures. The mercuric sulfide precipitates as black HgS and is determined easily by filtering, drying and weighing. The method is convenient and rapid; use of H_2O_2 as the oxidizing agent avoids introducing substances which interfere with subsequent steps in the procedure.

Analyses in the ternary system HgS–Na_2S–H_2O.—Saturated solutions were filtered by forcing them through a glass filter stick immersed in the solution by applying air pressure to the surface of the liquid. The filtered solution was caught in a polyethylene bottle, cooled, and transferred to a weight buret. Each sample was divided into several portions and weighed into beakers. The solutions were diluted with water, and dilute H_2O_2 was added. The HgS precipitate was caught in fritted glass crucibles and dried at 110°C until constant weight was attained. The Na_2S percentages were obtained by two methods: (1) analysis of the filtrate for sodium in the form of Na_2SO_4; and (2) analysis of the filtrate for sulfate, in the form of $BaSO_4$. Analysis for sodium was accom-

plished by evaporating the filtrate to dryness, transferring the Na_2SO_4 salt to a platinum crucible, dessicating and weighing according to the procedure in Furman (1939, p. 878). Sulfate was determined by precipitating as $BaSO_4$ and weighing (Kolthoff and Sandell, 1943, p. 340-341).

Analyses of solutions containing known amounts of HgS are presented in table 7. The average difference between the weight of HgS determined by analysis and the known weight was about 0.1 percent of the sample weight, with the maximum difference about 0.3 percent. In table 8 analyses of solutions for Na_2S carried out by the Na_2SO_4 method are compared with analyses carried out by the $BaSO_4$ method. The two methods yielded results which agree well.

Analyses in the quaternary system HgS–Na_2S–Na_2O–H_2O.—The additional component, Na_2O, was determined in solutions of the quaternary system in the following way. As in the ternary system, the filtered saturated solution was divided into several portions, weighed into beakers, and dilute H_2O_2 was added. After the reaction had reached completion, the solutions were neutralized carefully with dilute HCl, and the HgS was filtered off by means of fritted glass crucibles, dried, and weighed. The filtrate, which contained NaCl, Na_2SO_4, and H_2O_2, was evaporated to dryness to expel H_2O_2 and any excess HCl present. The resulting mixture of NaCl and Na_2SO_4 was dissolved in water, transferred to a platinum crucible, and evaporated to dryness over a water bath. The salt mixture was dehydrated by careful heating, after which it was cooled and weighed to determine the combined weight of NaCl and Na_2SO_4. The salt mixture was then dissolved in water and analysed for sulfate by the barium sulfate method used in the ternary system. The Na_2S percentage of the original sample and the weight of the Na_2SO_4 in the salt mixture were both calculated from the weight of the barium sulfate. Subtracting the weight of the Na_2SO_4 from the weight of the NaCl–Na_2SO_4 mixture yielded the weight of NaCl in the mixture. The Na_2O percentage of the original sample was calculated from the weight of NaCl. The reproducibility of the results of the procedure, tested on different portions of the same sample, was found to be excellent.

TABLE 7

Analyses of Solutions Containing Known Amounts of Mercuric Sulfide

Weight of HgS Taken g.	Weight of HgS by Analysis g.
0.4437	0.4438
0.3947	0.3942
0.8272	0.8282
1.0327	1.0338
0.3086	0.3083
0.3887	0.3899
0.5087	0.5100
0.2766	0.2765
0.3183	0.3180

TABLE 8

Comparison of Na_2S Percentages Obtained from Analyses for Sodium as Sodium Sulfate with Na_2S Percentages of the Same Solutions Obtained from Analyses for Sulfate by the Barium Sulfate Method

Weight % Na_2S from Na_2SO_4 Method	Weight % Na_2S from $BaSO_4$ Method
3.57	3.57
3.58	3.58
1.50	1.50
6.07	6.03
6.06	6.08
4.37	4.37
	4.39
5.03	5.09
2.89	2.85
6.56	6.54
10.91	10.94

Table 9 presents analyses of solutions containing known amounts of NaCl and Na_2SO_4. The average difference between known weights of NaCl and the experimentally determined weights was about 0.1 percent.

TABLE 9

Analyses of Solutions Containing Known Amounts of NaCl and Na_2SO_4

Weight Na_2SO_4 taken	0.4044	0.2100
Weight NaCl taken	0.0631	0.2266
Combined weight	0.4675	0.4366
Analytically determined combined weight	0.4668	0.4363
Analytically determined weight of Na_2SO_4	0.4033	0.2098
Analytically determined weight of NaCl	0.0635	0.2265

EXPERIMENTAL RESULTS

The experimental work of this investigation included the determination at one atmosphere pressure of the solubilities of red HgS and of black HgS in aqueous Na_2S solutions in the ternary system HgS–Na_2S–H_2O at 25°C, 50°C, and 75°C, and the solubility of red HgS in Na_2S–NaOH solutions in the quaternary system HgS–Na_2S–Na_2O–H_2O at 25°C and 75°C.

Ternary system HgS–Na_2S–H_2O.—The saturation curves of red HgS (cinnabar) and black HgS (metacinnabar) in the portion of the system HgS–Na_2S–H_2O ranging from 75 to 100 percent H_2O were determined at 25°C, 50°C, and 75°C. Tables 10 and 11, and figures 1 and 2 present the experimental data.

Black HgS is more soluble than red HgS throughout the temperature range 25°-75°C. The solubilities of both forms decrease with increasing temperature, but the solubility of black HgS decreases at a greater rate than does the solubility of red HgS. The ratio of dissolved HgS to total Na_2S increases with increasing concentration of Na_2S.

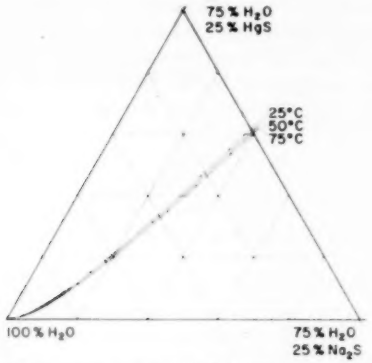

Fig. 1. The saturation curves of red HgS (cinnabar) in a portion of the system HgS–Na_2S–H_2O at 25°C, 50°C, and 75°C.

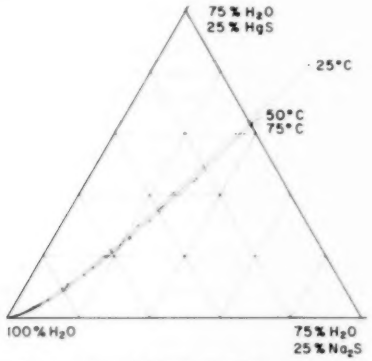

Fig. 2. The saturation curves of black HgS (metacinnabar) in a portion of the system HgS–Na_2S–H_2O at 25°C, 50°C, and 75°C.

TABLE 10

Solubility of Red HgS (Cinnabar) in Aqueous Na_2S Solutions

25°C			50°C			75°C		
Weight % HgS	Weight % Na_2S	Weight % H_2O	Weight % HgS	Weight % Na_2S	Weight % H_2O	Weight % HgS	Weight % Na_2S	Weight % H_2O
0.27	0.92	98.81	0.42	1.22	98.36	0.22	0.92	98.86
0.74	1.58	97.68	1.33	2.28	96.39	0.80	1.82	97.38
1.02	1.88	97.10	2.38	3.18	94.44	1.14	2.22	96.64
2.23	2.92	94.85	7.38	6.39	85.73	2.85	3.62	93.53
3.84	3.99	92.17	15.43	9.85	74.72	8.79	7.02	84.19
11.69	7.89	80.42				10.82	8.03	81.15
13.85	8.86	77.29				13.50	9.15	77.35

TABLE 11

Solubility of Black HgS (Metacinnabar) in Aqueous Na_2S Solutions

25°C			50°C			75°C		
Weight % HgS	Weight % Na_2S	Weight % H_2O	Weight % HgS	Weight % Na_2S	Weight % H_2O	Weight % HgS	Weight % Na_2S	Weight % H_2O
0.11	0.51	99.38	0.44	1.09	98.47	0.94	1.72	97.34
0.79	1.37	97.84	2.51	2.90	94.59	1.39	2.17	96.44
2.76	2.85	94.39	4.98	4.43	90.59	2.24	2.89	94.87
7.56	5.37	87.07	8.99	6.33	84.68	3.45	3.64	92.91
10.24	6.55	83.21	9.12	6.39	84.49	4.03	3.97	92.00
20.70	10.93	68.37	15.90	9.26	74.84	6.57	5.33	88.10
						7.94	6.03	86.03
						11.17	7.55	81.28
						11.37	7.59	81.04

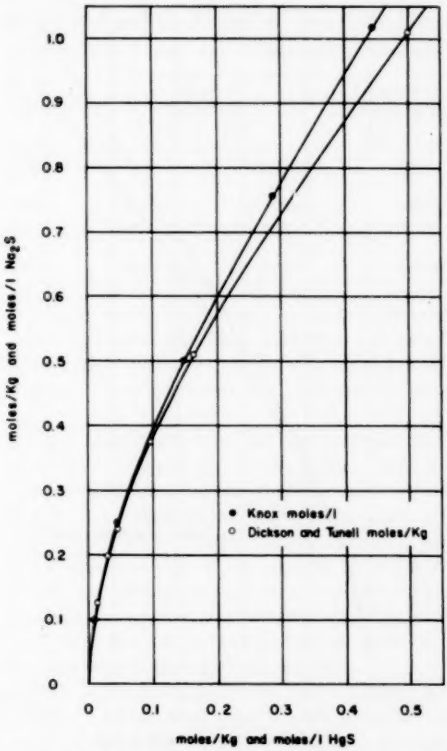

Fig. 3. Comparison of Knox's data for the solubility of red HgS (cinnabar) in aqueous Na_2S solutions at 25°C, expressed in moles per liter of solution, with those of Dickson and Tunell at 25°C, expressed in moles per kilogram of solution.

Knox (1906) studied the solubility of red HgS and black HgS in Na_2S solutions at 25°C and 33°C, at one atmosphere pressure. Knox's 25°C data, expressed in moles per liter, are presented in table 1. Our data calculated in moles per kilogram of solution for comparison purposes are presented in table 12. Figures 3 and 4 show Knox's and our values for red HgS and black HgS, respectively. The curves coincide at low Na_2S concentrations and diverge at higher concentrations.

The two sets of data are in reasonable agreement so far as can be determined. The divergence of the curves at higher Na_2S concentrations is probably caused by two effects, one involving the manner in which Knox's experimental procedure differed from ours, and the other, a matter of expressing concentrations in different ways. Knox did not determine the final concentration of Na_2S, but only the final concentration of HgS. Solutions usually increase in volume on dissolving a solid, thus causing a lowering of the concentration of

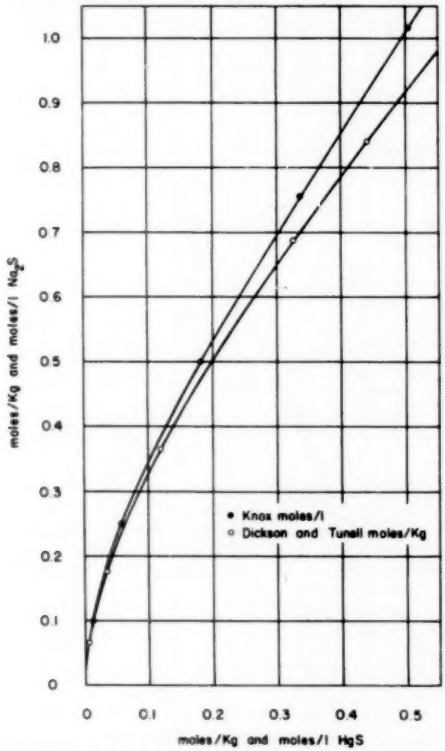

Fig. 4. Comparison of Knox's data for the solubility of black HgS in aqueous Na_2S solutions at 25°C, expressed in moles per liter of solution, with those of Dickson and Tunell at 25°C, expressed in moles per kilogram of solution.

TABLE 12

Solubility of Red HgS (Cinnabar) and Black HgS (Metacinnabar) in Na_2S Solutions at 25°C Determined by Dickson and Tunell

Red HgS		Black HgS	
Final Conc. Na_2S Moles/kg	Final Conc. HgS Moles/kg	Final Conc. Na_2S Moles/kg	Final Conc. HgS Moles/kg
1.136	0.591		
1.010	0.501	1.402	0.889
0.511	0.1650	0.840	0.440
0.374	0.0956	0.689	0.325
0.241	0.0438	0.365	0.1185
0.202	0.0318	0.1757	0.0339
0.118	0.0116	0.0654	0.00472

TABLE 13

Solubilities of Red and Black HgS in Na_2S at 25°C and 50°C, Determined by Dickson and Tunell, and Temperature Coefficients of Solubility

	Na_2S Mole/kg	HgS Mole/kg 25°C	HgS Mole/kg 50°C	Concentration Difference	Percent Change per °C
Red HgS	0.641	0.244	0.228	−0.016	−0.26
	0.385	0.1070	0.0997	−0.0073	−0.27
Black HgS	0.641	0.295	0.268	−0.027	−0.37
	0.385	0.1284	0.1142	−0.0142	−0.44

any substance initially present; the change in volume increases directly as a function of the amount of solid dissolved. Therefore, Knox's Na_2S concentrations are probably too high compared to the true equilibrium concentrations, resulting in a difference which increases as a function of increasing Na_2S concentration.

Even if Knox had determined the final concentration of Na_2S his curves would be expected to diverge from ours at the higher Na_2S concentrations because his data are expressed in moles per liter and ours are in moles per kilogram. The relation between the two modes of expression is: moles/liter = moles/kg × density (in kg/liter). Therefore, the two ways of expressing concentration would be equivalent only if the density were one, that is infinitely dilute solution. In solutions of higher concentrations and higher densities quite different values for the same solution will be obtained if the concentration is expressed in moles per liter than if it is expressed in moles per kilogram. The difference will be greater the higher the concentration.

Our temperature coefficient of solubility for red HgS, about 0.3 percent per degree C (table 13), agrees well with Knox's for solutions ranging from about 0.8 to 0.3 moles per liter Na_2S (table 3). Saukov obtained a higher value for the temperature coefficient of solubility of black HgS, 0.66 percent per degree C (table 5), than our value for black HgS, 0.40 percent per degree C

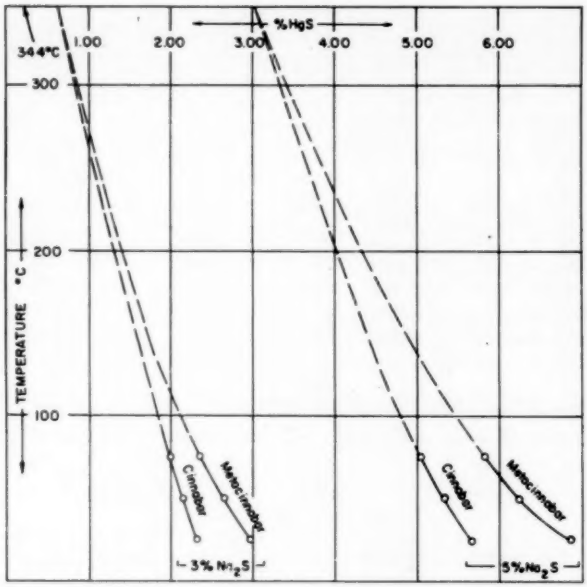

Fig. 5. Constant Na_2S sections (5% Na_2S and 3% Na_2S respectively) through the saturation surface of red HgS (cinnabar) and the saturation surface of black HgS (metacinnabar) in a portion of the system HgS–Na_2S–H_2O. The broken lines represent the upward extrapolated curves drawn to intersect at 344°C, the inversion temperature of red and black HgS.

(table 13). Saukov's 17°C data are inaccurate, however, and therefore his temperature coefficient is unreliable.

The solubilities of both red and black HgS decrease with increasing temperature. Black HgS is more soluble than red HgS at all three temperatures, but the solubility of black HgS decreases at a greater rate than the solubility of red HgS. Figure 5 shows two sections of constant Na_2S concentration (five and three percent Na_2S) through the temperature-composition saturation surface. A greater decrease in the solubility of black HgS with rising temperature implies that at some elevated temperature its solubility becomes equal to that of red HgS. At this temperature the two forms of HgS could coexist stably in contact with the same solution, and hence would be in equilibrium with each other. Above this temperature metacinnabar would be the more stable modification. Unfortunately, the equilibrium (or inversion) temperature cannot be determined from the solubility data by extrapolating upward because the angle of intersection of the curves is small, and slight experimental inaccuracies or incorrect extrapolation would greatly change the inferred temperature. By direct methods, however, we have determined the temperature at which red and black HgS can coexist in equilibrium at one atmosphere pressure to be 344°C

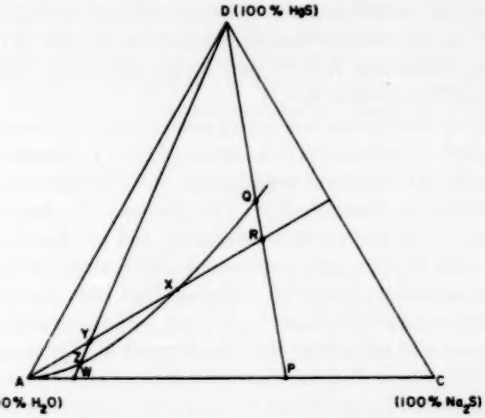

Fig. 6. Illustration of the effects of dilution and evaporation of saturated solutions in the system HgS–Na_2S–H_2O; point X represents a saturated solution of HgS in aqueous Na_2S, point Y saturated solution plus crystalline HgS, and point R unsaturated solution. Not drawn to scale.

(unpublished work). Figure 5 shows in broken lines extrapolated portions of the curves, drawn to intersect at the determined inversion temperature.

Although the solubility of HgS decreases with increasing temperature, upward extrapolation of the data shows that in the range from 100°C to 200°C the solubility remains of the same order of magnitude as at 75°C. A moderate increase of temperature therefore, does not rob Na_2S solutions of their capacity to contain HgS.

Diluting saturated solutions of HgS in Na_2S precipitates HgS. If a saturated solution, represented by point X in figure 6, is diluted with water, the points representing the equilibrium composition of the solution will move along the saturation curve toward the 100 percent water corner. The point representing the total composition of the system (solution and solid phase) will move into the two phase field above the curve, to some point such as Y, along a line joining the original point on the saturation curve with the H_2O corner. The ratio of the amount of HgS precipitated by the dilution to the amount remaining in solution is given by the ratio of line segment YZ to the line segment ZW.

Evaporating saturated solutions of HgS in Na_2S increases the solubility of HgS. If the saturated solution represented by point X in figure 6 is isothermally evaporated, the point representing the composition of the solution moves directly away from the water corner along the extension of the line joining point X with the water corner, to some point such as R in the unsaturated solution field. The solution thus becomes capable of dissolving additional HgS. The ratio of the amount of HgS needed to saturate the solution to the amount of HgS in the solution is given by the ratio of line segment QR to line segment RP.

Any process which has the effect of removing Na_2S from the system will precipitate HgS. Processes which are capable of removing Na_2S are: oxidation

of Na_2S to Na_2SO_4; acidification, which converts Na_2S to NaHS; and reaction of Na_2S with substances other than HgS which are capable of forming a complex ion more stable than $HgS_2^{=}$, such as the reaction of sulfur with $S^{=}$ to form the polysulfide complex $S_n^{=}$.

Summary of conclusions concerning relations in the ternary system.—The solubility of HgS in aqueous Na_2S is increased by: (1) increasing the concentration of Na_2S; (2) isothermal evaporation; and (3) decreasing the temperature. The solubility is diminished by: (1) dilution; (2) decreasing the Na_2S concentration; (3) increasing the temperature; and (4) making Na_2S unavailable to react with HgS by such processes as acidification, oxidation, or by reaction with a substance capable of displacing HgS from the $HgS_2^{=}$ complex.

Quaternary system HgS–Na_2S–Na_2O–H_2O.—The saturation surfaces of red HgS in the portion of the system HgS–Na_2S–Na_2O–H_2O ranging from 75 percent H_2O to 100 percent H_2O have been determined at 25°C and 75°C, at one atmosphere pressure. Tables 14 and 15 present the numerical values of the experimental data. The data are represented in figures 7 and 8 as points in a regular tetrahedron orthogonally projected onto the base of the tetrahedron, the HgS–Na_2S–H_2O face. The saturation curve for red HgS in the sub-system HgS–Na_2S–H_2O is also included for comparison purposes. Figures 9 and 10 present constant Na_2O sections through the saturation surfaces projected onto the base of the tetrahedron.[1]

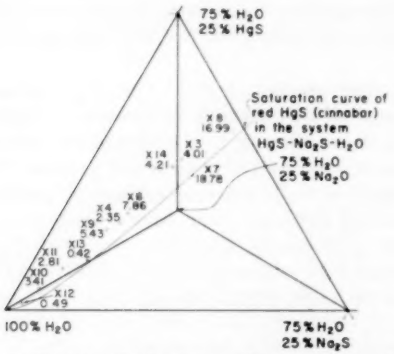

Fig. 7. Experimentally determined points on the saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O at 25°C, orthogonally projected onto the face HgS–Na_2S–H_2O of the regular tetrahedron HgS–Na_2S–Na_2O–H_2O. The centers of the small circles are the projected points; and the Na_2O percentage for each point is listed alongside the point. The coordinates of the points were taken from table 15. The saturation curve of red HgS in the system HgS–Na_2S–H_2O is drawn on the face HgS–Na_2S–H_2O.

[1] Detailed information on graphical methods used in drawing the curves are included in the appendix of: Dickson and Tunell, 1955, Geochemical and petrographic aspects of mercury ore deposits, Final Report, O.N.R. 233 (12), Project NR 081-174.

Adding the component Na_2O (in the form of NaOH) to Na_2S solutions markedly increases the solubility of red HgS. The mole ratio of dissolved HgS to Na_2S approaches the value one as the concentration of NaOH is increased, keeping Na_2S constant. The solubility of HgS diminishes if the Na_2O or Na_2S concentration is decreased, if the temperature is raised, or if the solution is diluted.

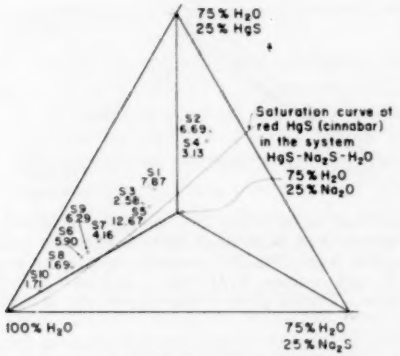

Fig. 8. Experimentally determined points on the saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O at 75°C, orthogonally projected onto the face HgS–Na_2S–H_2O of the regular tetrahedron HgS–Na_2S–Na_2O–H_2O. The centers of the small circles are the projected points; and the Na_2O percentage for each point is listed alongside the point. The coordinates of the points were taken from table 16. The saturation curve of red HgS in the system HgS–Na_2S–H_2O is drawn on the face HgS–Na_2S–H_2O.

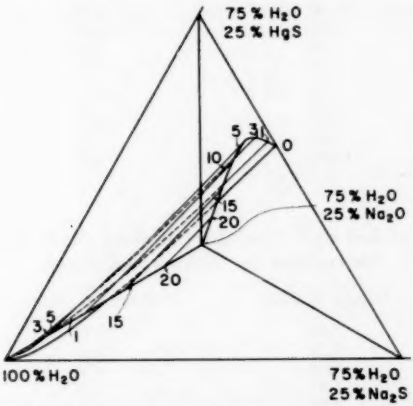

Fig. 9. Constant Na_2O curves in the 25°C saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O, orthogonally projected onto the face HgS–Na_2S–H_2O; the 25% Na_2O–75% H_2O corner is toward the reader. The percentage of Na_2O appropriate to each constant Na_2O curve is indicated at both ends of the curve; each constant Na_2O curve is dashed where it passes under the saturation surface as viewed from above.

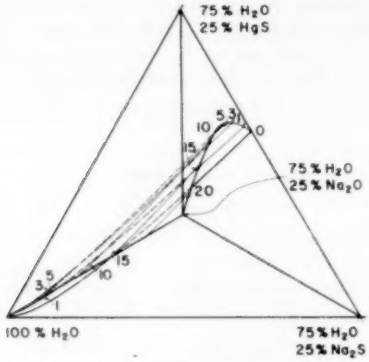

Fig. 10. Constant Na_2O curves in the 75°C saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O, orthogonally projected onto the face HgS–Na_2S–H_2O; the 25% Na_2O–75% H_2O corner is toward the reader. The percentage of Na_2O appropriate to each constant Na_2O curve is indicated at both ends of the curve; each constant Na_2O curve is dashed where it passes under the saturation surface as viewed from above.

TABLE 14

The Solubility of Red HgS (Cinnabar) in Na_2S–Na_2O Solutions at 25°C Determined by Dickson and Tunell

Weight % HgS	Weight % Na_2S	Weight % Na_2O	Weight % H_2O
0.38	0.70	0.49	98.43
0.66	0.36	3.41	95.57
2.52	1.43	2.81	93.24
4.07	3.66	0.42	91.85
4.56	1.81	8.35	85.28
4.99	1.72	18.78	74.51
5.03	2.20	5.13	87.64
5.55	2.16	7.86	84.43
9.49	3.35	16.99	70.17
10.66	4.69	4.21	80.44
11.42	5.03	4.01	79.54

TABLE 15

The Solubility of Red HgS (Cinnabar) in Na_2S–Na_2O Solutions at 75°C Determined by Dickson and Tunell

Weight % HgS	Weight % Na_2S	Weight % Na_2O	Weight % H_2O
1.15	1.00	1.71	96.14
2.58	1.21	5.90	90.31
2.86	1.34	6.29	89.51
3.13	2.35	1.69	92.83
4.58	2.33	4.16	88.93
4.65	1.79	12.67	80.89
7.69	3.10	7.87	81.34
8.25	4.56	2.58	84.61
12.91	5.12	6.69	75.28
13.35	6.43	3.13	77.09

The velocity of the transformation of black HgS to red HgS is increased to such an extent in strongly alkaline solutions that it proved impractible to determine the solubility of black HgS in them.

The saturation surfaces of red HgS in the system HgS–Na_2S–Na_2O–H_2O at each temperature has the shape of an asymmetric saddle, with the sharpest curvature near the water corner and near the base of the tetrahedron. Constant Na_2O lines in the saturation surfaces are convex toward the unsaturated solution field (figs. 9 and 10).

Tables 16 and 17 present graphically derived data for the solubility of red HgS in Na_2S solutions at 25°C and 75°C, at various Na_2O percentages. The strong increase in the solubility of red HgS in Na_2S solutions to which NaOH has been added is revealed by the data of tables 16 and 17. Increasing temperature decreases the solubility of red HgS in the quaternary system to about the same extent as in the ternary system over the same temperature interval. Figure 11 shows 3 percent Na_2O sections through the 25°C and 75°C saturation surfaces. Adding or removing water from saturated solutions in the quaternary system produces similar effects to those in the ternary system. Adding water, keeping the ratio of Na_2S to Na_2O constant, causes precipitation of HgS; removing water causes saturated solutions to become unsaturated. Figures 12a and 12b show the 90 percent H_2O and the 97 percent H_2O sections through the 75°C saturation surface. The saturation curve for the lower H_2O concentration, 90 percent H_2O, is relatively closer to the HgS corner than the saturation curve for 97 percent H_2O, which indicates that red HgS is more soluble in the 90 percent H_2O solution for a given ratio of Na_2S to Na_2O. Dilution of a saturated solution on the 90 percent H_2O curve represented by point X in figure 12a to 97 percent H_2O causes the solution to change to a composition represented by X′ in the 97 percent H_2O section. Point X′ falls in the saturated solution plus

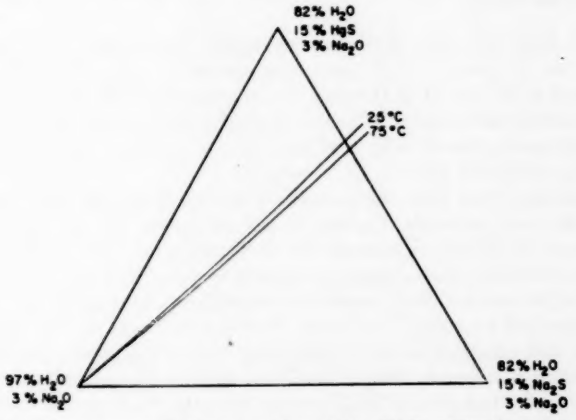

Fig. 11. Three percent Na_2O sections through the 25°C and 75°C saturation surfaces of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O showing the decrease in solubility with increasing temperature.

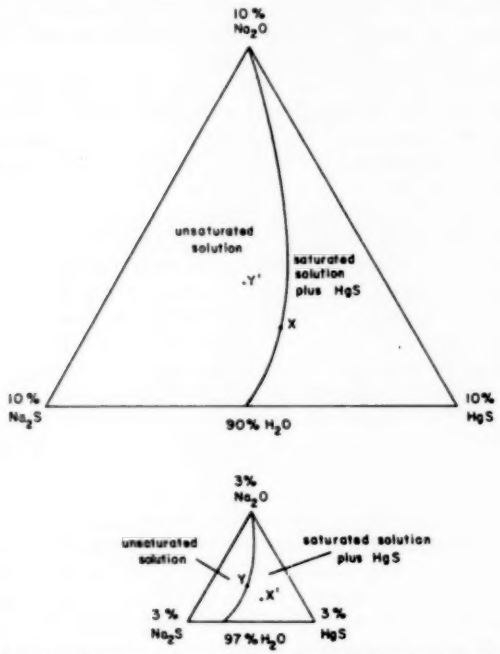

Fig. 12a & 12b. Constant water sections (90% H_2O and 97% H_2O respectively) through the 75°C saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O.

red HgS field; therefore, HgS must precipitate. Conversely, a saturated solution on the 97 percent H_2O curve, represented by point Y in figure 12b, evaporated to 90 percent H_2O causes the composition of the solution to change to that represented by point Y′ in the 90 percent H_2O section. Point Y′ falls in the unsaturated solution field, and represents a solution which is capable of dissolving additional HgS.

Removing Na_2S from the quaternary system causes the solubility of red HgS to decrease markedly. Figures 13 and 14 present five percent Na_2S and two percent Na_2S sections through the 75°C saturation surface. Reducing the Na_2S concentration of a solution represented by point P in figure 13 from five percent to two percent Na_2S causes the composition of the system to change to that represented by point P′ in figure 14. Point P′ lies in the two phase field, red HgS and saturated solution. Therefore HgS precipitates when the Na_2S concentration is reduced. Adding Na_2S to a solution represented by point Q in figure 14 in the two percent Na_2S section, until the Na_2S concentration is five percent, causes the composition of the system to change to that of Q′ in figure 13 in the five percent Na_2S section. Point Q′ falls in the unsaturated solution field, and therefore the solution becomes capable of dissolving more HgS.

The constant Na_2S sections through the saturation surface are concave toward the unsaturated solution field; the concavity toward the unsaturated solution field does not mean that evaporation will cause HgS to precipitate, however. Removal of H_2O causes the composition of the system to move directly away from the 100 percent H_2O corner, out of the constant Na_2S plane into the unsaturated solution field.

Adding Na_2O to Na_2S solutions greatly increases the solubility of red HgS (tables 16 and 17). The ratio of percent Na_2S to percent HgS in the saturated solutions decreases with increasing Na_2O and Na_2S concentrations. Figure 15

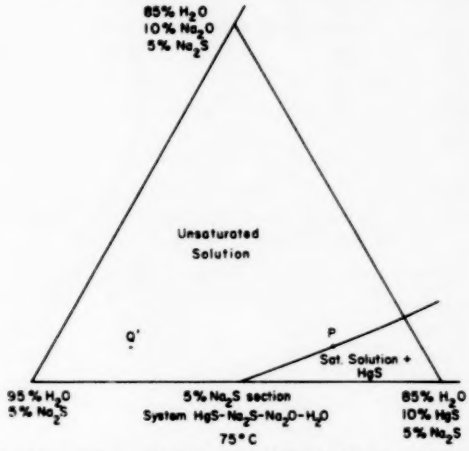

Fig. 13. Constant sodium sulfide section (5% Na_2S) through the 75°C saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O.

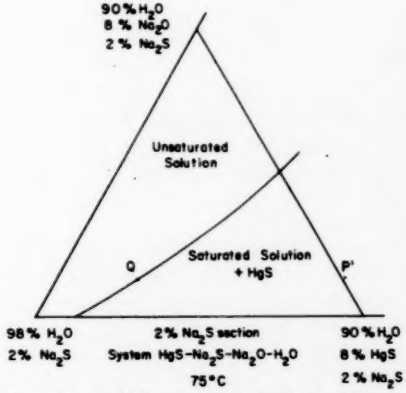

Fig. 14. Constant sodium sulfide section (2% Na_2S) through the 75°C saturation surface of red HgS (cinnabar) in a portion of the system HgS–Na_2S–Na_2O–H_2O.

TABLE 16

Graphically Derived Solubility of Red HgS (Cinnabar) in Na_2S–Na_2O Aqueous Solutions at 25°C

Weight % Na_2S	Weight % HgS in					
	0% by Weight Na_2O	1% by Weight Na_2O	3% by Weight Na_2O	5% by Weight Na_2O	10% by Weight Na_2O	15% by Weight Na_2O
1.00	0.32	0.89	1.81	2.14	2.47	2.66
2.00	1.11	2.20	3.80	4.53	5.08	5.59
3.00	2.32	3.89	5.99	6.99	7.70	8.56
4.00	3.91	5.78	8.28	9.45	10.44	11.62
5.00	5.67	7.87	10.52	12.64	13.38	
6.00	7.65	9.92	12.87	14.74		
7.00	9.75	12.07	15.34			
8.00	11.97	14.30				
9.00	14.10					

TABLE 17

Graphically Derived Solubility of Red HgS (Cinnabar) in Na_2S–Na_2O Solutions at 75°C

Weight % Na_2S	Weight % HgS in				
	0% by Weight Na_2O	1% by Weight Na_2O	3% by Weight Na_2O	5% by Weight Na_2O	10% by Weight Na_2O
1.00	0.28	0.82	1.56	1.98	2.40
2.00	0.97	2.01	3.40	4.20	4.91
3.00	1.98	3.48	5.36	6.54	7.55
4.00	3.39	5.06	7.46	9.00	10.25
5.00	5.06	6.89	9.75	11.56	
6.00	6.80	8.86	12.15	14.21	
7.00	8.72	11.05	14.60		
8.00	10.81	13.30			
9.00	12.93	15.62			

presents curves illustrating the variation of the Na_2S to HgS ratio with Na_2S concentration at several Na_2O concentrations. A one to one mole ratio of Na_2S to HgS corresponds to a ratio of the percentages of 0.3354. This value is closely approached in the concentrated Na_2O and Na_2S solutions saturated with HgS. Knox's postulate of a one to one mole ratio of Na_2S to HgS in the complex anion thus seems reasonable.

Knox's data on the solubility of HgS in Na_2S–NaOH solutions (table 2) show an apparent increase in the Na_2S–HgS ratio with increasing Na_2S concentration in his strongest NaOH solutions. Our data do not show the same effect. This increase implies that evaporating strongly alkaline solutions would eventually cause some HgS to precipitate. We evaporated such solutions in vacuo to dryness, and no red or black HgS was detected in the resulting colorless mat of hygroscopic crystals. The crystals were probably a mixture of NaOH, Na_2S, and Na_2HgS_2, or their hydrated forms.

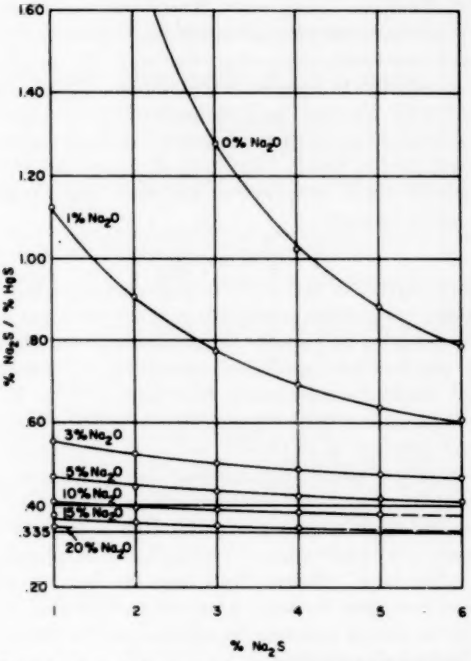

Fig. 15. The variation of the ratio of weight percent Na_2S to weight percent HgS with changing Na_2S percentage, at different Na_2O percentages, in solutions saturated with red HgS (cinnabar) in the system HgS–Na_2S–Na_2O–H_2O at 25°C. The numerical data used for the construction of the curves were taken from table 17.

Knox's apparent reversal appears to be a consequence of his neglecting to determine the final concentrations of Na_2S and Na_2O actually in equilibrium with HgS. He determined the final concentration of HgS only, together with the initial concentrations of Na_2S and Na_2O. Knox's data can be converted approximately to weight percent on the assumption that the volume change is negligible when HgS dissolves in Na_2S and NaOH of known initial concentration. If this assumption be made for Knox's 1.015 and 0.1 molar Na_2S solutions that were 7.7 normal in NaOH, it turns out that his supposedly constant 7.7 normal NaOH solutions varied from 15 percent by weight Na_2O (20 percent by weight NaOH) for the 1.015 molar Na_2S solution to 18 percent by weight Na_2O (24 percent by weight NaOH) for the 0.1 molar Na_2S solution. The increase in the ratio of the percent Na_2S to percent HgS caused by decreased Na_2S percentage would be compensated for by the decrease in the ratio caused by increased Na_2O percentage. If, as appears likely, an increase in volume attended the dissolving of HgS in Na_2S–NaOH mixtures, Knox's initial Na_2S and NaOH concentrations are too high for the corresponding final HgS concentrations; the amount of the discrepancy would be a function of the

amount of HgS dissolved. Consequently, Knox's ratio of Na_2S to HgS would not show the correct decrease with increasing Na_2S concentration.

Summary of conclusions concerning relations in the quaternary system.—The solubility of red HgS in aqueous Na_2S solutions is markedly increased by the presence of NaOH. The mole ratio of dissolved HgS to total Na_2S increases as a function of increasing NaOH concentration and approaches unity in solutions most concentrated in NaOH. The effects of change in water concentration (evaporation and dilution), temperature, and Na_2S concentration are similar to those in the ternary system.

CONCLUSIONS

The primary purpose of this paper is to present the results of the laboratory investigations, but it seems reasonable at this point to present some tentative inferences concerning the possible nature of mercury ore-forming solutions. Alkaline Na_2S solutions are capable of transporting geologically significant amounts of HgS within the temperature interval of 25°C to 75°C; extrapolation to higher temperatures indicates that HgS is sufficiently soluble at 150°C for alkaline Na_2S solutions to be possible ore carrying solutions. Mercuric sulfide will not precipitate from saturated solutions as a consequence of a drop in temperature. Dilution of saturated solutions will precipitate HgS. Saturated or initially unsaturated solutions may precipitate HgS as the result of oxidation, reaction with more acidic solutions, or by reaction with substances in the wall rock, such as sulfur, which displace HgS from the $HgS_2^=$ complex. Studies carried out by us and other workers of natural precipitation of cinnabar and metacinnabar at the surface and near the surface indicate that all the processes suggested are geologically possible.

ACKNOWLEDGMENTS

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DISCUSSION

KYANITE-SILLIMANITE EQUILIBRIUM AT HIGH TEMPERATURES AND PRESSURES—DISCUSSION

R. D. SCHUILING

The November issue of the AMERICAN JOURNAL OF SCIENCE (v. 255, p. 628-641) brings an interesting publication on the phase-relationships between the aluminosilicates (Clark, Robertson, and Birch, 1957). Although their experiments were carried out under P-T conditions which are only of limited interest to metamorphic petrology, it is evident that they constitute a most welcome addition to our knowledge about the behavior of these minerals. However, I wish to offer a few criticisms in relation to a paper which I recently published on the same subject (Schuiling, 1957).

In this paper, the P-T conditions prevailing during the formation of sillimanite, kyanite and andalusite in many natural occurrences were determined as well as possible, and the values obtained were plotted on a P-T diagram. A statistical phase-diagram of Al_2SiO_5 was obtained by this method. This diagram (here reproduced as fig. 1) may be the first quantitative approach to this problem. When comparing its features with those of the phase-diagram provided by Clark, Robertson and Birch (their fig. 3), some discrepancies may be observed, even if allowance is made for the qualitative character of the latter. Also, it seems that the diagram given by the cited

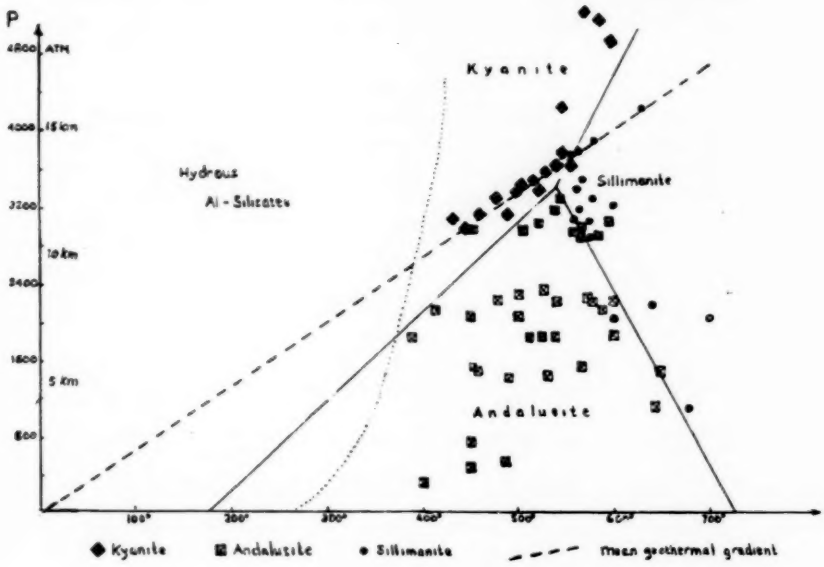

Fig. 1.

authors is largely incompatible with field evidence. The following considerations about Clark, Robertson and Birch's diagrams are of interest in this matter.

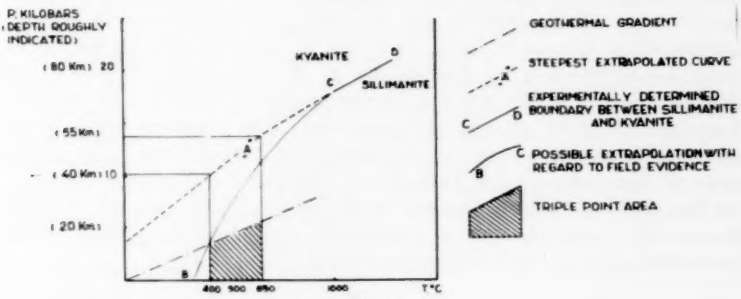

Fig. 2.

1. The steepest boundary (curve "A" of fig. 2 herewith; steepest curve of their table 4) between kyanite and sillimanite which they allow shows a positive intercept with the pressure axis at 3650 bars (as stated in the table) or 3350 bars (as stated in the text). Although the extrapolated boundary is metastable in this part of the diagram, it is clear that the triple-point will lie somewhere on this boundary between the points T = 0°, P = 3650 bars and T = 1000°, P = 18,200 bars, which is the first experimentally determined point of this line. The writers accept the coexistence of the three aluminosilicates as evidence of a triple-point (just as I did in my paper). Examination of the metamorphic facies of rocks in these critical occurrences, however, shows that the temperature of formation must have been somewhere between 400° and 650°, allowing for a wide divergence of opinion (surely most petrologists would already agree upon 500° to 600°). These are temperatures which are reached in the Earth's crust between 12 and 20 km depth, and which correspond roughly to pressures between 2500 and 5000 bars. The fact that andalusite is absent from true regional metamorphic regions proves that the triple-point must be located somewhere between 400° and 650° at the high-temperature side of a line indicating the geothermal gradient. This is shown by the shaded area in figure 2 which, apart from this area, shows the experimentally determined part of Clark, Robertson and Birch's diagram as well as their steepest, extrapolated kyanite-sillimanite boundary. The triple-point, however, must be a point on the boundary-line between kyanite and sillimanite. By connecting any point of the shaded area in figure 2 with the experimentally determined part of the boundary-line (for example line BC in fig. 2), it is shown that the pressure-intercept is negative, so that kyanite will be the stable phase under surface conditions. If it is accepted that the coexistence of the three phases in nature would prove the presence of a triple-point near the conditions of metamorphism for this association, it is not admissible to locate this triple-point at or above the extrapolated "A"-curve,

which, as a matter of fact, would require a minimal depth of burial between 40 and 55 km (see fig. 2).

2. The apparently wrong extrapolation of the experimental facts led the writers to another distortion of the metamorphic picture. They duly remarked that in many a metamorphic region the outer zones are occupied by kyanite, whereas sillimanite can be found in the central parts. This distribution can be easily accounted for by my diagram (fig. 1). However, Clark, Robertson and Birch are forced to attribute this arrangement to the existence of (strong) horizontal gradients, meaning that abnormally high pressures would be required in the outer zones and/or abnormally high temperatures in the central parts. It seems strange that these strong gradients should always occur according to the special case required by the writers. On the contrary, it might be expected that a variation of temperature and pressure according to the geothermal gradient would be the normal case.

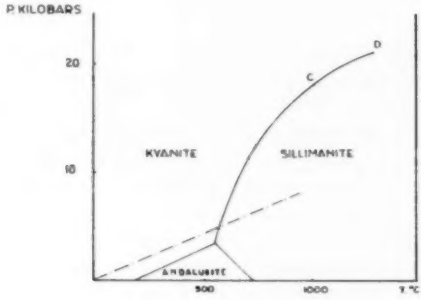

Fig. 3.

In short, it is to be feared that Clark, Robertson and Birch were too much impressed by the results of their excellent laboratory-work and, accordingly, paid too little attention to the facts of metamorphic petrology. Maybe the combination of their experimental data with my diagram would provide the nearest approach to truth which is possible at the moment (see fig. 3). The slope of the kyanite-sillimanite boundary line in figure 3 has been changed somewhat, compared to the original diagram (fig. 1), in order to obtain a better correlation between the two sets of data. The original boundary line had been determined on thermodynamical considerations, which are always apt to contain a certain element of uncertainty, owing to extrapolation of data obtained at room conditions.

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REPLY

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Confusion as to what facts concerning metamorphic petrology may be directly inferred from field observations is apparent in Dr. Schuiling's comments on the experimental work in the kyanite-sillimanite system. It seems clear that the scale of temperatures and pressures which he uses to fix the points of his diagram, based on his table 1 (Schuiling, 1957) depends upon (1) a highly indirect and possibly faulty correlation with laboratory studies of other mineral associations, and (2) upon assumptions regarding the pressure-temperature relationships during metamorphism. The temperatures of the metamorphic isograds do not show in the field and are probably dependent on other variables than pressure alone. Thus the basis of his own diagram, the scale of his table 1, established by round-about connections with other laboratory studies, is hardly to be accepted as "field evidence" in contradiction with our relatively direct laboratory study.

Reactions involving phases of variable composition are generally not univariant. Reactions involving the release of volatiles depend on the fugacities of those volatiles, which in many cases are not uniquely determined by temperature and total pressure alone. In such cases isograds cannot be represented by lines on the P-T plane. Still less can they be said to determine points on this plane, as in Schuiling's table 1; these "points" are all on his "normal" pressure-temperature line, which is used to determine the conditions for regional metamorphism (Rule II). Nearly all the kyanite occurrences are plotted on this line. This procedure introduces the assumptions that the pressure-temperature relation is everywhere the same, and that it is given by a straight line which leads to 1200°C at the base of a 35-km crust. Both of these assumptions are unacceptable; observations of temperature show large differences at given depths, and the temperature at 35 km probably does not normally exceed 600°C or so. If the temperatures assumed for the kyanite points are correct, the corresponding pressures are considerably higher than 3 or 4 kilobars. All this assumes more knowledge of the pressure-temperature relations during regional metamorphism than we really possess.

Our suggestion that horizontal temperature gradients would account for the appearance of sillimanite in the central (hotter) part of a metamorphosed region, with kyanite in the outer (cooler) part, at a given level (pressure) is criticized, perhaps because of a misunderstanding as to what was intended. Exactly the same assumption is necessary to explain this relationship with Schuiling's phase relations.

In order to get any points which do *not* plot on his "normal" temperature-pressure line (e.g., all the andalusite points and most of the sillimanite points), Schuiling has recourse to estimates of pressures and temperatures during contact metamorphism (Rule III), presumably reflecting "abnormal" conditions; these estimates also depend upon the excessively high "normal" temperatures, which are used to establish the local pressure at the time of contact metamorphism. They have little bearing on the kyanite-sillimanite equilibrium.

The position of the triple point presumably corresponds to conditions which can be realized in the crust, but otherwise remains unknown. It is not fixed by the experimental work. Unless the projection of the kyanite-sillimanite curve to lower temperatures has much more curvature than seems consistent with the measurements of heat capacity, the triple point must lie at a pressure not lower than about 3,000 bars (the pressure intercept at 0°C). Our diagram, which is only schematic with respect to andalusite, was drawn with the work of Roy (1954) and Kennedy (1955) in mind, as well as the general relationships pointed out by Miyashiro (1949) and Thompson (1955). It does not seem to us that geologic data provide a more definite position. The experimental determination of the triple point would be of considerable interest.

It is, of course, regrettable that the observations of the kyanite-sillimanite transformation could not be followed to lower temperatures and pressures. These are exceedingly refractory compounds, and we were gratified that they could be dealt with even over a limited range of the variables. The possibility that equilibrium has not been reached, inherent in all such studies, is probably higher than usual for this system, and will doubtless interest other investigators. The large uncertainties in the extrapolation to lower temperatures were emphasized in our paper; there seems to be no reason for believing that the curvature need be so great as suggested by Schuiling's diagram (fig. 3 of "Discussion").

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REVIEWS

Einführung in die geometrische und physikalische Kristallographie und in deren Arbeitsmethoden, 3d ed.; by FRANZ RAAZ and HERMANN TERTSCH. P. xii, 367; 384 figs. Wien, 1958 (Springer-Verlag, $11.45).—The first and second editions were entitled "Geometrische Kristallographie und Kristalloptik, and had about 215 pages. The changes and additions represent an improvement on an already good treatment. New footnote references throughout the book will permit a serious student to pursue points of interest further with less research. A more extended discussion of structural crystallography and x-ray analysis brings the balance of the crystallographic section better into line with modern thinking and modern methods, though the discussion of x-ray techniques should include brief mention of moving-film methods and methods using the Geiger counter or other electronic detectors of x-rays.

Tertsch's part on physical crystallography is much expanded over the corresponding part on crystal optics in the old editions; a theoretical and practical, but brief, treatment of physical properties (ca. 46 pp) includes elasticity, cleavage, hardness, specific gravity, and electrical, thermal, and magnetic properties. The description and measurement of optical properties forms the main part of physical crystallography.

Although the International symmetry symbols for the point groups are explained, their extension to the space groups is hardly touched, and the Schoenflies symbols are used throughout.

The book as a whole is a distinct improvement over the earlier editions, and its authors should be congratulated for a good job; it will find places in the reference libraries of many mineralogists and crystallographers, and probably wide use as a general text.

HORACE WINCHELL

Graphic Methods In Structural Geology; by WILLIAM L. DONN and JOHN A. SHIMER. P. viii, 183; 103 figs. New York, 1958 (Appleton-Century-Crofts, Inc., $4.00).—Geologists have long used the orthographic projection, supplemented with trigonometry, to analyze spatial configurations of folds and faults in the earth's crust, but only within recent years have they begun to give equal attention to the stereographic projection. Here for the first time on this side of the Atlantic is a book that directs a major share of its attention to this tool which is so useful in attacking problems involving angular relationships of rock layers.

Compact and well-planned, this little volume is in three parts, each consisting of seven to nine chapters covering individual topics. The first part, a 58-page section describing bedded rocks, is quite elementary, and will be useful primarily to beginning students. The next section of 64 pages and nine chapters, reviews the principles of orthographic projection, then by examples illustrates step-by-step the methods used in solving different sorts of problems. The third and last part—seven chapters covering 40 pages—does the same with the stereographic projection.

Three appendices complete the book. One describes the construction of an ellipse. Another presents three alignment diagrams, all after Palmer, relating (1) true dip, apparent dip, and the angle between strike and section; (2)

width of outcrop, thickness, and dip; and (3) distance, depth to bed, and dip. The third appendix comprises a selected bibliography of 25 entries.

The book is well written. Explanations are lucid, reflecting careful attention to details of sentence structure and meaning. One discordant note for some, however, will come from the indiscriminate use of *data* with both singular and plural verb forms. Dictionaries and crotchety reviewers still prefer that only *datum* be used with singular verbs.

More than 100 figures enhance the value of the book. Most have been carefully drawn, and wherever possible, placed opposite the reading matter which they illustrate.

Toward the end of the book, however, several steps are commonly compressed into one figure, usually a stereonet diagram, resulting necessarily in omission of certain measurements. This provides some mental gymnastics, and many would prefer that numerical values be given for each step. For instance, in addition to writing (page 142), " . . . lay off an arbitrary pitch angle AD along the appropriate meridian circle," it would be an improvement to state the value of the pitch angle used in the drawing.

In a few instances different parts of the same figure have inadvertently been printed with different scales. Diagram D of figure 30 (page 147) has a scale larger than that of the rest of the figure. This drawing is properly credited "after Bucher," but the original, which appeared in the Journal of Geology, May 1944, has a correctly uniform scale. Diagram C of figure 91 (page 149) is reversed and also printed with a scale different from the rest of the figure. But there are remarkably few such mistakes, considering the many drawings and numerous chances for errors.

Exercise questions are provided at the ends of many of the chapters. No answers are given, a fact which some may regret, but serious students will still find such questions useful.

In all, the book provides excellent material both for teaching the principles of orthographic and stereographic projection, and for reviewing such principles whenever thinking becomes a bit rusty.

HALL TAYLOR

Suggestions to Authors of the Reports of the United States Geological Survey, 5th ed. P. xii, 255, Washington, 1958 (Government Printing Office, $1.75).—The new fifth edition of *Suggestions to Authors* will be welcomed by geologists throughout the country, not only or especially by Survey members but also and perhaps even more by professors and editors. Generations of fledgling geologists have found marginal references to the earlier editions in their manuscripts; they will now be referred to the new edition, and most of them (and their elders as well) should have a personal copy. What can be done by one book to hold the line against inexact and sloppy writing, this book has done and will continue to do.

The new edition is twice the size of its predecessor and, though from five to ten times the price (depending on when one bought the previous edition), still a bargain. The increase in size reflects a large increase in scope; moreover the old material has been completely rearranged in a more logical order, so

that the two editions are not easily compared offhand. Much of the increase results from more thorough discussions of different kinds of reports (on water resources, on mining districts, on mineral reserves), and of different kinds of terminology; the section on geologic names is particularly full and, though the rules advocated are mainly those needed to enforce consistency in a large organization like the Survey, they can be read with profit by anyone, however individualistic. By contrast, the section entitled "Suggestions as to expression" is very little larger than before, though better organized (discussing words and phrases alphabetically instead of in related groups is not an improvement, however). The new index is much fuller than the old and should be very useful.

Whereas the older editions were largely the work of two individuals, the new edition is the work of a committee; the admirable increase in scope is a direct result. Nonetheless one familiar with the fourth edition will miss something; many of the old-favorite horrible examples are still there, but somehow the old bite has weakened, the old flavor is dissipated. The individuals who prepared the earlier editions were gifted stylists as well as fine editors, and *their* writing was not flattened out by repeated editing. In the new edition, one senses the safe, sane, cautious approach; any dangerously imaginative expressions met with somebody's disapproval, and the resulting style, like that of so many Survey reports, is adequate but somewhat flat and in a few places just a little stuffy. But this is the price that had to be paid for the fuller coverage and more consistent arrangement.

From now on, the AMERICAN JOURNAL OF SCIENCE will consider the new edition of *Suggestions to Authors* the standard in most matters of form and of expression. In particular we will follow with care the form of citation there advocated, which is based on the recommendations of a committee of editors (including representatives from both the Survey and the JOURNAL) and which is now followed by a considerable number, if not a majority, of American geological publications. Authors submitting articles to the AMERICAN JOURNAL OF SCIENCE will save both themselves and us trouble and delay if they will (own and) make use of this invaluable book.

JOHN RODGERS

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